University of Alberta

SIMULATION AGGREGATE PLANNING FOR BATCH PLANT SUPPLY CHAIN

by

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Abstract

Aggregate planning is an important method in supply chain management to increase competition in the market. On the other hand, aggregate planning also ties up a great deal of capital and exerts a strain on customer service. Batch plant supply chain differs significantly in its characteristics from other supply chains, with its members forming unique interrelationships. Quantifying the gains and losses associated with employing different alternatives requires modeling the batch plant supply chain. This thesis presents research in the development of a simulation template in a *Simphony* environment which provides aggregate planning a tool to optimize and coordinate the entire supply chain. The simulation template also integrates and specifies different characteristics of the batch plant supply chain. After that the thesis focuses on the application of a batch plant supply chain simulation template by modeling asphalt production operations, which can be regarded as a typical batch plant supply chain. A varying and uncertain demand pattern affects the economics of asphalt production facilities and makes the design of the production and inventory processes a challenging task. The simulation model is developed to assist in reconfiguring and optimizing the inventory and production processes of an existing asphalt plant in order to meet variations in the demand pattern of this plant. The results from the models are used to analyze the sensitive factors involved in aggregate planning for the asphalt production process. Finally, the results generated from the simulation model are compared to the results generated from a linear programming model, which is a classical method for aggregate planning. The advantages of the simulation model are exhibited by comparison to this traditional method.

To my parents, Xingyuan and Xiaoyan

For their love, encouragement, and continued support

Throughout my entire education

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1. Introduction

1.1 Overview

Aggregate planning, which improves efficiency and coordination, is an important method in supply chain design. Aggregate planning allows managers to proactively manage demand and supply to ensure that the productivity and profits are maximized. Based on the demand, the production process, inventory level, and distribution process are all changed to maximize integration and coordination within the entire supply chain. Several techniques are employed in the development of aggregate plans, such as a graphical method and linear programming. Unfortunately, a number of problematic assumptions and constraints are associated with using these techniques to develop aggregate planning. These assumptions and constraints oversimplify the real system and fail to correctly reflect the actual situation such that an accurate result cannot be generated (AbouRizk 1990).

Batch plant, such as asphalt plant or concrete plant, in construction industry is a central location at which cement, water, aggregates and selected admixtures are mixed to make asphalt or concrete. The batch is loaded to trucks through silos, used to transport the fresh asphalt or concrete to the construction site. With respect to the batch plant, its supply chain differs significantly in its characteristics from other supply chains. For instance, the production method is make-to-order instead of make-to-store. However, little attention has been paid to aggregate planning within a batch plant environment, and thus a method for developing aggregate planning in batch plant supply chain needs to be developed. Simulation models capture a situation, and then allow further elaboration and investigation (Sawhney and Abudayyeh 1999). Due to the complex and unique relationship among the members of the batch plant supply chain, simulation models are to be preferred over mathematical models as a means to planning such situations.

This research aims at developing a batch plant supply chain template integrated with aggregate planning as a methodology to optimize and coordinate the entire supply chain. This template was developed in a *Simphony* environment and a simulation model for an existing asphalt plant to be considered as a case study was built using the template. A varying and uncertain demand pattern affects the economics of asphalt production and makes the design of inventory level, production process, and distribution process a challenging task. This simulation model was developed to assist in reconfiguring and optimizing the asphalt plant supply chain to meet variable demand patterns. The model simulates the demand on a daily basis and the plant responses to this demand under different production plans, distribution plans, and inventory capacities.

1.2 Research Objectives

The objective of this research is to develop a simulation template as a tool to facilitate the use of aggregate planning in a batch plant. Using this template, a simulation model is built for an existing asphalt plant's operations. The results of the study provide a means of reconfiguring and optimizing inventory level, production process, and distribution process to meet the variable demand patterns of this plant. In order to achieve these objectives, five steps have been identified:

- Understand the concepts and ideas of the aggregate plan. Improve and specify the methodology for the batch plant.
- Develop a special purpose simulation template for batch plant supply chain.
- Validate the batch plant supply chain template's performance using the results of a proven model.
- Build a simulation model for an existing asphalt plant.
- Present sensitivity analysis of the results in order to capture the sensitive factors and optimize inventory level, production process, and distribution process; compare the simulation results with the linear programming results.

1.3 Thesis Organization

Chapter 2 provides the summary of scholarly literature pertaining to the concepts of supply chain, aggregate planning, and the linear programming model (a classical tool for aggregate planning). The chapter then briefly introduces supply chain simulation models and simulation tools. From the literature review, this chapter formulates the problems and challenges, which are met in utilizing aggregate planning in batch plant supply chain and outlines the research objectives of this thesis.

Chapter 3 discusses the development of the simulation template. It includes an explanation of the proposed template, the definition of the constraints and assumptions, as well as a full description of each modeling element and its function.

Chapter 4 uses the HKCONSIM, a simulation modeling program for Hong Kong's ready mixed concrete (RMC) production operations, as a case study to validate the batch plant supply chain template developed in Chapter 3. The simulation model built by the template uses the same input model and data as HKCONSIM. The differences between the outputs of the two simulation models are also presented in this chapter.

Chapter 5 of this thesis uses the validated simulation template to develop a simulation model for an existing asphalt plant. It includes a problem description, a special model development, output sensitivity analysis, and output comparisons between the simulation model and the linear programming model.

Chapter 6 of this thesis describes the conclusions, contributions, and recommendations for future research.

2. Literature Review

2.1 Introduction

The literature review presented below is intended to introduce concepts, ideas, strategies and definitions related to aggregate planning and moreover to characterize aggregate planning as an area of particular interest to this thesis research.

Section 2.2 reviews the basic concepts of supply chain and supply chain management. Section 2.3 reviews the strategies and classical tools of aggregate planning. Section 2.4 details the constraints and shortcomings of the linear programming model for aggregate planning and identifies the research objective in this thesis. Section 2.5 presents a survey of the literature related to supply chain simulation modeling. Section 2.6 offers a brief summary of computer simulation algorithms and modeling techniques, focusing particular attention on *Simphony*. Section 2.7 presents a summary of the literature and survey the research field which is the simulation modeling of aggregate planning for batch plant supply chain.

2.2 Supply Chain

The supply chain is the network of organizations involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services for the consumer (Christopher 1998).

As extrapolated from the definition, a supply chain consists of all stages involved, either directly or indirectly, in fulfilling a customer request. The supply chain not only includes the manufacturers and suppliers, but also transporters, warehousers, retailers, and the customers themselves. Within each of these representative parties, the supply chain includes all functions involved in receiving and filling a customer request (Chopra and Meindl 2007).

Supply chain management (SCM) can be defined as "A set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouse and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying system level requirements" (Simchi-Levi et al. 2003).

SCM requires taking into consideration each activity, either within a firm or between firms, which has on impact on fulfilling the customer's expectations. SCM is a set of system approaches to design, plan, maintain, and operate supply chain process for the satisfaction of the end-user's needs (Ayers 2004). This set of approaches is applied with the aim of integrating all of these activities in the supply chain. The ultimate objective of applying these approaches is to maximize efficiency across the entire supply chain (Khorramabady 2006).

The primary objective of the research presented in the thesis does not support all aspects of SCM but focuses on aggregate planning only.

2.3 Aggregate Planning

As the term *aggregate* implies, aggregate planning means combining the appropriate resources into general terms. Given the demand input, facility capacity, overall inventory levels, size of workforce, and related inputs, aggregate planning specifies output in terms of the work hours, inventory level, and productivity required to meet customer demand (Heizer et al. 1997). The main purpose of aggregate planning is to synchronize the flow of materials along the supply chain. Aggregate planning also supports decisions on the efficient utilization of production, transport, supply capacities, seasonal stock, as well as on the balancing of supply-and-demand (Fleischmann et al 2005). As a result of this synchronization, production and distribution entities are able to make the whole supply chain more efficient and profitable.

The goal of the following context is to explain the strategies and the classical tool, linear programming, of aggregate planning.

2.3.1 Aggregate Planning Strategies

Aggregate planning is an important issue with respect to supply chain management. In order to be effective, it requires inputs from all elements within the supply chain, and its results have a tremendous impact on supply chain performance. First of all, expected demand is an important input for aggregate planning which directly impacts the accuracy of the results. In addition, many constraints as key inputs in aggregate planning come from both up and down stream of the supply chain (Chopra and Meindl 2007). Without these inputs, aggregate planning cannot realize its full potential to create value.

Key information, specified as follows, is required as input for aggregate planning and in order to make the decisions for which the aggregate planning will develop recommendations (Hugos 2006):

- **Demand input:** demand data as a basis input of the aggregate planning
- **Machine production rate:** the number of units to be completed per unit time
- **Inventory holding:** the planned inventory carried over the various periods in the planning horizon
- **Workforce:** the number of workers/units of machine capacity needed for production
- **Constraints:**
  - Limits on overtime
  - Limits on layoffs
  - Limits on subcontract
  - Limits on storage capacity
  - Constraints from suppliers to the enterprise
  - Constraints from customers to the enterprise

Aggregate planning strategies involve the manipulation of inventory, production rate, labor levels, and capacity. These five variables are to be regarded as trade-offs in aggregate planning. In order to meet customer demand, increasing one of these variables

serves to reduce the others. Arriving at the most coordinate and integrate combination of trade-offs is the goal of aggregate planning. Given that demand varies over time, the relative level of the five factors leads to one of them being identified as the key factor in meeting customer demand.

The five strategies are as follows (Heizer et al 1997).

1. *Changing Production rate:* With this strategy, the production rate is synchronized with the demand rate. This is achieved by adding or eliminating plant facilities as needed. In practice, achieving this synchronization can be very problematic because of the difficulty of varying facilities on short notice. This strategy can be expensive to implement if the cost of varying machinery over time is high.

2. *Varying Total Work Hours:* This strategy can be utilized if excess work time is available (i.e., machines are not used 24 hours a day, seven days a week). In this case, the production rate is kept stable but the work hours are varied over time in an effort to synchronize production with demand. A planner can use variable amounts of overtime or a flexible schedule to achieve this synchronization. This strategy results in low levels of inventory, constant facilities and workforce, as well as high average levels of overtime.

3. *Using Inventory and Backlogs:* With this strategy, stable work hours, workforce and production rate are maintained with a constant rate. However, production is not synchronized with demand in this case. Either inventories are built up during periods of low demand in anticipation of future demand or inventories are allowed to run low and backlogs are built up in one period to be filled in a subsequent period. This strategy results in lower costs of changing capacity but it does generate large inventories or backlogs over time as demand fluctuates.

4. *Subcontracting:* A plant can handle peak demand period by subcontracting some work. Subcontracting, however, poses several problems. Most importantly,

subcontracting has a high cost. Second, as a regular practice it risks opening the door of your client to a competitor.

5. *Changing workforce*: Another way to meet customer demand is to hire or lay-off workers to match production needs, (i.e., hiring new employees in peak demand periods and laying-off in periods of low demand). However, the training of new employees is costly. It is also often disruptive and demoralizing to the workforce if people are repeatedly being hired or fired as demand rises and falls.

Using the key information input in conjunction with these strategies, a company makes determinations through aggregate planning. The key purpose of the aggregate planning is to specify the particular combination of production rate, workforce level, and inventory on-hand, which serves to both minimize costs (efficiency) and satisfy demand (effectiveness). The following determinations are specified for a generic aggregate planning problem (Davis and Heineke 2005):

- **Machine capacity increase/decrease:** determine whether new production equipments should be purchased or idled
- **Workforce hired/laid off:** determine any labor issues likely to be encountered
- **Backlog/Stock-out Quantity:** determine customer service levels
- **Inventory held:** determine the warehouse space and working capital required
- **Production quantity form regular time, overtime, and subcontracted time:** determine number of workers and supplier purchase levels

The quality of an aggregate plan has a significant impact on the batch plant's profit. A poor aggregate plan can result in lost sales and lost profits if the available inventory and capacity are unable to meet demand. A poor aggregate plan may also result in a large amount of excess inventory and capacity, thereby raising costs. As such, aggregate planning is a very important tool for managing batch plant supply chain.

2.3.2 Linear Programming Model for Aggregate Planning

As discussed earlier, the goal of aggregate planning is to meet customer demand. Every company, in its bid to achieve this objective, faces certain constraints, such as the capacity of its facilities or a supplier's ability to deliver a component. Linear programming as a classical tool for aggregate planning is used to achieve objective while being subjected to a series of constraints. In other words, linear programming finds the solution that meeting customers' demand and satisfying the constraints that the company faces.

In a supply chain, a number of activities, such as production or transportation, compete for resources. The available quantities of resources may be insufficient to accommodate all of the demands placed on them. Linear programming models allow resources to be allocated across the entire system being analyzed in order to determine how scarce resources can be optimally used (Shapiro 2007). Linear programming models widely employ mathematical techniques to develop aggregate planning and make the decisions necessary to allocate resources. All Linear programming models have four properties in common (Heizer 1997):

1. Linear programming models seek to maximize or minimize some quantity, such as profit or cost. This property is referred as the objective function of a linear programming model. The major objective of a typical plant, for instance, is to maximize profit and customer service levels in the long run.

2. The presence of restrictions or constraints limits the degree to which the objective can be pursued. For example, deciding on how many tons of concrete to manufacture in a plant's product line is restricted by available labor and machinery.

3. There must be alternative courses of action from which to choose. For example, if an asphalt plant produces three different mixes, the linear programming model is used to decide how to allocate among them with limited resources.

4. The objective and constraints in the linear programming model must be expressed in terms of linear equations; as such, Microsoft Excel is one of the tools to facilitate the linear programming model.

Generally, the first step in constructing a linear programming model is to identify the set of decision variables whose values are to be determined as part of the aggregate planning. The second step is to define clearly the constraints linked with the decision variables in the aggregate planning. The final step is to define the objective function. The objective function is to balance inventory, demand, production, and distribution in order to meet customer demand.

2.4 Constraints and Shortcomings

Based on the literature review, we find that aggregate planning is an important strategy in SCM. Using the linear programming model as the classical tool for aggregate planning is both efficient and simple. On the other hand, several constraints are applied in the linear programming model, which somehow oversimplify the real system and cannot correctly reflect the actual situation. These constraints and shortcomings directly result in the value of aggregate planning being limited.

First, the linear programming model only focuses on obtaining a feasible production plan subject to constraints arising from demand and available capacity. However, it does not provide a tool which can select an optimal solution from among the feasible production plans, based on objectives. The linear programming model generates the judged solutions rather than comparing the relationships between two or more variables.

Second, the classical tool formulates the aggregate planning problem as a linear program in order to obtain a production schedule for each period of time but cannot incorporate nonlinear optimization to account for the fact that not all constraints or reasonable objective functions are linear functions.

Thirdly, a linear programming model cannot handle switch time between multiple products. On the other hand, the batch plants in the construction industry offer flexibility options for the customer to produce multiple products with the same equipment. Since the general purpose equipment is shared between several products, switch time cannot be ignored in the batch plant aggregate planning.

A linear programming model also fails to represent the orders from different customers according to priority. In fact, in real situations, some orders must always take priority over others.

The coordination between production and distribution is also critical. While it is clear that an integrated aggregate plan should be adopted in order to maximize total benefits and avoid potential conflicts, little theoretical work can be found in the literature to inform such integrated aggregate planning. Indeed, most works in aggregate planning do not deal with distribution explicitly. Usually, distribution is taken as unlimited such that the effect of distribution cannot be determined. Thus the aggregate planning reduces to a standard production plan without distribution affecting the entire supply chain.

The linear programming model includes the control of inventory levels, which is only considered as the buffer between constant production and variable orders in order to meet customer demand. However, the important questions in inventory management are intended to determine the timing of the replenishment and the size of inventory, with reference to two variables, replenishment quantity and baseline quantity (Verma 2005). The replenishment quantity controls the order-up-to level that is maintained so as to avoid excessive replenishment costs. The baseline quantity affects the safety inventory level maintained in order to avoid backlog (Cheng 1996). With added baseline and replenishment inventory control, aggregate planning models can add significant value for the supply chain. Unfortunately, little literature can be found to deals with optimizing baseline and replenishment quantity of inventory in aggregate planning.

Given the complexity of the aggregate planning model, there is often no other way to arrive at a feasible solution than through a simulation model. To address these shortcomings in linear programming models, the objective of the research presented in this thesis is to develop a computerized simulation model for aggregate planning, which can generate optimal inventory level, production plan, and distribution plan. The aggregate plan can handle multi-product orders with varied priorities. The aggregate plan can also take into account all variables in both linear and nonlinear functions and compare the relationship between two or more variables.

2.5 Simulation Models for SCM

The simulation model is undoubtedly one of the most powerful techniques to apply here, thanks to its predictable features. It is flexible and economical to reproduce and to test different decision-making alternatives in tangible scenarios, in order to produce an optimal and coordinated plan in advance (Terzi and Cavalieri 2003). The use of a simulation model in place of a linear programming model serves to resolve the constraints and shortcomings of aggregate planning development outlined above. The goal of this section is to review and discuss the various simulation models which have been built for SCM and to try to uncover a solution for batch plant SCM based on previous research work. Unfortunately, no simulation model can be found to exactly represent the batch plant supply chain or generate an aggregate plan which overcomes the constraints and shortcomings mentioned in the last section. Finally, the research objectives of this thesis can be determined, which is the development of a simulation model for aggregate planning in batch plant supply chain.

In this section, three classification criteria have been adopted for categorizing the reviewed simulation models:

- Objective
- Scope
- Development stage

1. Objective: These simulation models are related to the specific objectives which can be highlighted with two major objectives.

a) *Network supply chain design*: Simulation can be used as a decision support system within the design phases. It stands for logical modeling and production process configuration. For example, in the work of Tiger and Simpson (2003), a specific supply chain simulation model is designed for a technology-based company. Several complex resources associated with the problem and the need for a flexible solution necessitate that the authors choose a simulation model to design supply chain regarding direct shipping from US-based consolidation point in order to achieve economical load factor.

b) *Supply chain strategic decision support*: Simulation is applied over a supply chain to evaluate more strategic alternatives (Terzi and Cavalieri 2003). A simulation model is constructed for a concrete batch plant using the Micro CYCLONE simulation system. Based on the sensitivity analysis, the model is applied to analyze alternative solutions and resource management in order to assist decision makers (Zayed and Halpin 2001).

2. Scope: The scope states the scale of the problems (strategic, tactic, operative) to be addressed by the simulation models. The classification makes use of the same categorization of supply chain planning (Terzi and Cavalieri, 2003).

a) *Supply and demand planning*: Ming et al. (2003) developed approaches for construction simulation to model the one-plant-multisite ready mixed concrete (RMC) production system, HKCONSIM. This system is suitable for production planning and transportation planning of a RMC plant, so as to meet given demands at a number of sites for concrete over the course of a working day. The emphasis of the simulation modeling here is on the interactions of multiple sites and the plant, and the objective is to improve the supply service levels and the utilization of plant resources.

b) *Distribution and transportation planning*: IBM supply chain simulator is software intended to assist companies in making strategic decisions about the design and operation of their supply chain as well as providing modeling functions for distribution and transportation processes. This process models distribution center including finished goods inventory and material handling, transportation time, vehicle loading, and transportation cost (Bagchi et al. 1998).

c) *Production planning and scheduling*: Simulation process is designed to generate detailed production schedules for the shop floor over a relatively short interval of time. SDI is a simulation tool specifically developed for logistics chains which facilitates the development of models from single production machines to more complex distribution centers (Siprelle et al. 1999).

3. Development stage: Development stage refers to the different levels of development of applying the simulation models from the conceptual level to commercial applications.

a) *Conceptual level*: This level includes simulation models which still denote a conceptual content, since models here appear as not yet implemented or tested, but as proposals for new descriptive methodologies supporting the adoption of simulation in supply chain environments (Terzi and Cavalieri 2003). Van der Zee and Van der Vorst (2005) reviewed many simulation tools for supply chain and outlined their shortcomings, then proposing a new conceptual supply chain simulation framework. In this research, they proposed to use intelligent agents in simulation in order to model block capable of making decisions or adjusting parameters on its own.

b) *Software level*: At the software level, the features of tools specifically created for the design and development of simulation models are explained. Sawhney and Abudayyeh (1999) highlight the advanced features of petri nets and describe their utilization as a process modeling and analysis tool for the study of a ready-mix

concrete plant. With the advent of user-friendly and intelligent petri net software, decision makers and managers have at their disposal a useful decision tool to be employed in a wide variety of construction applications.

c) *Application level*: This refers to models which describe real applications of supply chain simulation. For example, Hwarng, Chong, Xie and Burgess (2005) use simulation to investigate the effects of several assumptions regarding the simplification of demand patterns and lead times in a wide variety of supply network structures. They have analyzed four different coordination policies and measured the benefits gained for each party involved in the network in terms of average stock level, backorder level, and cost.

2.6 Simulation Tools

Simulation is one of the powerful techniques to develop an aggregate plan for SCM, since the number of possible combinations of process interactions, interruptions, uncertainties, and other phenomena observed in the actual system often make supply chain complex and difficult to understand. On the other hand, developing a simulation model is not a trivial task and can be time consuming if the proper tools are not available (Fernando 2003). AbouRizk and Hajjar (1998) developed *Simphony* as a simulation platform to assist users in creating Special Purpose Simulation (SPS) templates for building simulation models. In this research, *Simphony* will be used as the platform upon which to build a simulation model for aggregate planning. The purpose of this section is to introduce *Simphony*.

Simphony represents an evolution in construction simulation. It consists of a foundation library, as well as specialized computer programs which allow for the development of new construction simulation tools in an efficient manner. Included is a large library of modeling elements available with the base distribution of *Simphony*. If any of the existing modeling elements are not flexible enough to meet certain modeling needs, or if new modeling elements need to be developed for different construction operations, then a

developer can create Special Purpose Simulation templates (Hajjar and AbouRizk 2002). *Simphony* is characterized by the following functions (AbouRizk, 2000):

- *Modular modeling*: The main model building block in *Simphony* is the modeling element. The user builds a simulation model in *Simphony* by creating instances of modeling elements that resemble real components of a construction system, and then linking them together in ways similar to those that exist in a real system.
- *Hierarchical modeling:* for representation of complex and large construction projects, *Simphony* provides a hierarchical modeling feature. A project can be represented by an abstracted model at higher levels. Each of these elements can have its own child model, which represents the sub-system working inside that element. The number of these hierarchical levels is only limited by the computer system's resources.
- *General purpose vs. special purpose simulation: Simphony* supports both general purpose modeling constructs (e.g.: CYCLONE), which can be used to model different construction processes, as well as specialized templates for specific construction methods (e.g., earth-moving and aggregate production), which are suitable for users with little simulation background.
- *Custom output results: Simphony's* modeling element can generate custom output results in the form of tables and graphs.
- *Automated generation of project planning data:* project planning data reflecting cost and time can be automatically generated by *Simphony* during simulation and presented to the user in a standard format.
- *Script-based modeling:* Script-based modeling allows advanced users wishing to bypass the graphical user interface to write a script to be processed by *Simphony* to handle advanced simulation behaviors.
- *User elements: Simphony* allows storage and retrieval of commonly used simulation model structures, known as "user elements", in the user elements library; these elements represent certain modeling elements with the complex internal structures or special parameter setting that are commonly used.

2.7 Conclusion

This chapter has reviewed the basic definitions of supply chain and SCM and explained the strategies of aggregate planning and the linear programming model. The constraints and shortcomings of the linear programming model have also been discussed. The simulation model was found to be a better method than the linear programming model for the development of aggregate planning. Existing simulation models built for SCM have been discussed as a means of finding a solution for batch plant SCM. Unfortunately, little research works refers to this area; furthermore, the research objectives of this thesis had to be set out. Finally, the simulation tool to be used in the modeling, *Simphony*, was introduced.

Based on the literature review conducted in this chapter, there are many limitations and constraints when using a linear programming model for aggregate planning. These constraints somehow oversimplify the real system and do not correctly reflect the batch plant supply chain. Given the complexity of the batch plant model, there is often no other way to arrive at a feasible solution than through a simulation model. However, the literature review shows that few simulation models have been developed for batch plant supply chain. Few models have been built as a tool to support integrated aggregate planning which combines production rate, inventory level, and distribution plan.

As a means of addressing these shortcomings, the objective of the research presented in this thesis is to develop a special purpose template for batch plant supply chain. The template will be used to build a simulation model for aggregate planning to synchronize and optimize the batch plant supply chain.

3. Development of Batch Plant Supply Chain Simulation Template

3.1 Introduction

In light of the concepts of aggregate planning described above, this chapter has three important purposes: to introduce the characteristics of batch plant supply chain, to explain the proposed methodology; and to develop a batch plant supply chain template.

Section 3.2 introduces the characteristics of batch plant supply chain in order that the different characteristics associated with this template might be addressed. Section 3.3 explains the proposed methodology used to develop the batch plant supply chain template, which includes three parts: demand input, aggregate planning, and constraints and assumptions. Section 3.4 details the parameters and outputs of each element in the batch plant supply chain template.

3.2 Batch Plant

There has been an increased interest in the design of batch processes in recent years due to the marked growth of the construction industry. Some of the products produced in batch facilities include concrete and hot mix asphalt. Batch plant supply chain can be distinguished from other supply chains by the following characteristics, which make SCM also unique.

- Batch plants are always multiple-product plants producing homogeneous mixtures. Multiple products imply similar operations and flow of materials. General purpose equipment offers the flexibility required to produce multiple products within the same facility, thereby reducing the operational costs of dedicated facilities (Subrahmanyam 1996).
- In the batch plant, since each task performed has a specific processing time, material transfer from one task to another is dictated by the precedence of the tasks at their start and finish times. This mode of operation is referred to as zero

wait. The distribution plan becomes a significant aspect of the batch plant supply chain which cannot be ignored (Subrahmanyam 1996).

- In batch processing, the operations involve sequencing and synchronizing supply and demand. Intermediate storage—in silos, for example— is used as a common factor between production and distribution in order to accommodate unsteady demand rates. Intermediate storage capacity could make the whole batch plant production capacity flexible enough to accommodate uncertain demand (Subrahmanyam 1996).
- All customers place their orders prior to production and decide on a pick-up day. The demand pattern makes the production plan based on the actual order. Make-to-order production method requires a batch plant to be sufficiently flexible, since orders are not stationary and are thus difficult to forecast in a make-to-order production method.
- Storage methods in the batch plant utilize silos or tanks, the features of which—such as layout and truck-loading constraints—vary from traditional warehouses.
- Due to the volatile nature of concrete and asphalt storage, the inventory cannot be held in the silos for any considerable length of time. The batch plant should also be distinguished from other plants in that it imposes constraints on the accuracy and synchronism of the production plan and distribution plan.

3.3 Proposed Methodology

The proposed template has two parts: demand inputting and aggregate planning (see Figure 3-1). For each part, parameters need to be inputted, whereas the output can be generated by the simulation model. With respect to the inputting of demand, the historical order information is stored in the simulation template. The order information is read from the database or statistical distribution and used to run the simulation model in *Simphony* environment. The criteria relationship and limitations of batch plant supply chain are preset in the simulation model. *Simphony* then generates the list of results for aggregate planning. Ultimately, the comparison charts and tables are created in Microsoft Excel. The details of each part will be explained specifically in the following portion of this section.

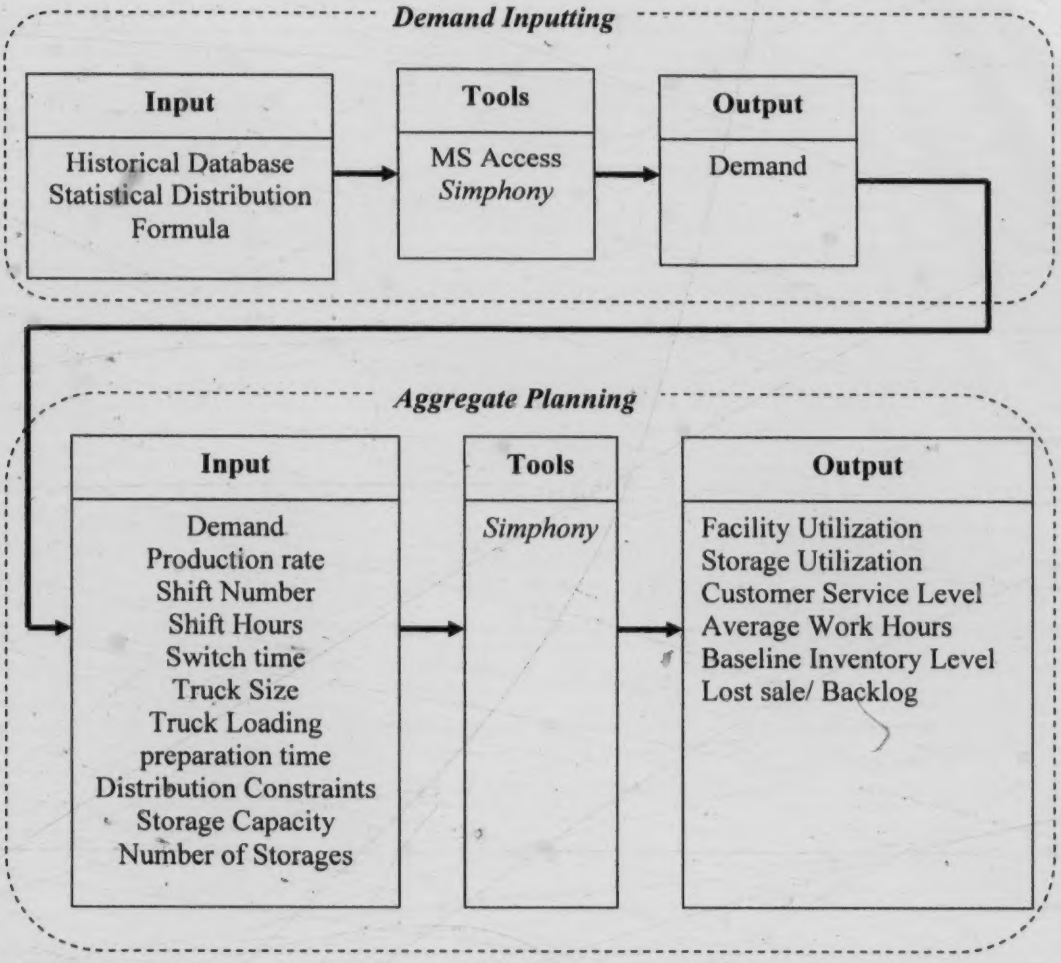

Figure 3-1 Proposed template process

3.3.1 Demand Inputting

Demand inputting is the first critical step in the batch plant supply chain model. Two methods used in this template, historical database and statistical distribution, are introduced below:

a) **Historical database**: Historical databases are the most appropriate source of input when future demand is related to historical demand. Observed demand can be

broken down into historical demand and trend factor. The raw data contained in the historical demand is stored in the database. Growth patterns that cannot be explained by historical demand are represented by trend factor in the formula as follows:

Observed Demand = Historical Demand * Trend Factor (Equation 3-1)

b) **Statistical distribution:** In this method, the demand can be randomly generated from a statistical distribution. By inputting the parameters, one of these distributions—constant, uniform, triangular, normal, exponential, or beta—can be defined. A formula also can be used to reflect the demand.

3.3.2 Aggregate Planning

Production, running hours, distribution, and baseline inventory level are four critical areas of aggregate planning in the batch plant supply chain template. The detailed methodologies used in the four areas are described below.

1. **Production**: Production is the main factor in aggregate planning. A large amount of excess capacity allows the facility to be very flexible and to respond to wide swings in demand; however, this practice implies high costs and therefore can decrease efficiency (Chopra and Meindl 2007). Limiting the capacity is economical but results in lost sales and backlog. Moreover, there exist two major methods in production.

- Make-to-order
- Make-to-stock

Make-to-stock is a production method scheduled according to the planning results, which is suitable for mass production of one product (Sen et al. 2004). Make-to-order is a production strategy used when customers' orders are received prior to production (Sen et al. 2004). Make-to-order is the method that has traditionally been employed within the construction industry for the batch plant. All customers place their orders before production and decide on the pick-up day. The batch plant prepares its daily production

planning based on daily customer orders. Orders are not stationary and thus are difficult to forecast under the make-to-order production method. In the batch plant supply chain template, make-to-order is the main production method used.

The following production-related factors influencing aggregate planning have been tracked.

- Production rate: measures the maximum product a facility can process in unit time.
- Utilization: measures the fraction of capacity that is currently being used (Chopra and Meindl 2007).
- Changeover/setup time: measures the average time that the facility devotes to changeover and setup.
- Customer service level: measures the faction of production orders completed on time and in full.
- Lost sale/backlog: measures the percentage of demand that fails to be satisfied on time and in full.

2. **Work Hours:** Work hours reflects the number of hours per day in which plants operate in order to satisfy customer demand. Since the production method is make-to-order in the batch plant, there are maximum work hours per day available rather than regular work hours. If work hours are greater than the maximum available work hours, overtime equals actual hours worked minus maximum available work hours. Maximum available work hours are obtained by multiplying shift hours by the number of shifts per day.

Overtime = Work hours – Maximum available work hours (Equation 3-2)

Maximum available work hours = Shift Number (per day) × Shift Hours (per shift) (Equation 3-3)

The following factors related to work hours and influencing the aggregate planning have been tracked.

- Average work hours: measures the average work hours needed to meet daily customer.
- Average overtime: measures the average amount of overtime needed to meet daily demand.
- Maximum available work hours: measures the capacity of daily work hours.

3. **Distribution:** Distribution comprises the flow of products from batch plants to a large number of customers. Distribution, which impacts both responsiveness and efficiency, is an essential part of the batch plant supply chain, because the batch plant needs to distribute customer demand on the exact day determined by the customer. If the batch plant is unable to fulfill customer demand, it will inevitably lose sales. Distribution also affects the production capacity with a limited storage capacity. If the distribution is not synchronic with production, production will be interrupted when all the silos are full. As mentioned above, the nature of the products to be stored—such as hot mix asphalt and concrete, the inventory cannot be held in the plant for a long period of time; if it is, the inventory will be spoiled. All of these factors make distribution a much more significant part of the batch plant supply chain than in the case of other supply chains. Two key components, distribution mode and distribution network, are analyzed below.

- *Distribution mode:* There are five basic modes which can be used—ship, rail, pipelines, trucks, and airplanes. Since almost all batch plants transport products by truck, this batch plant supply chain template focuses exclusively on truck distribution.
- *Distribution network:* Two options for distribution network, direct shipment and shipment through a distribution center, can be simulated individually or in combination within this template, as shown in Figure 3-2. With the direct shipment network option, the customers transport products directly from the batch plant. The major advantage of a direct shipment transportation network is the

elimination of intermediate storage space and the simplicity of operation. With the shipment though a distribution center, the customers are divided by geographic region with a distribution center built for each region. Batch plants transfer their shipments to the distribution center and the distribution center forwards appropriate shipments to the customer (Chopra and Meindl 2007). The benefit of shipment through a distribution center is that it can attract customers located far from the batch plant. The template can simulate these two options individually or in combination based on real project situations.

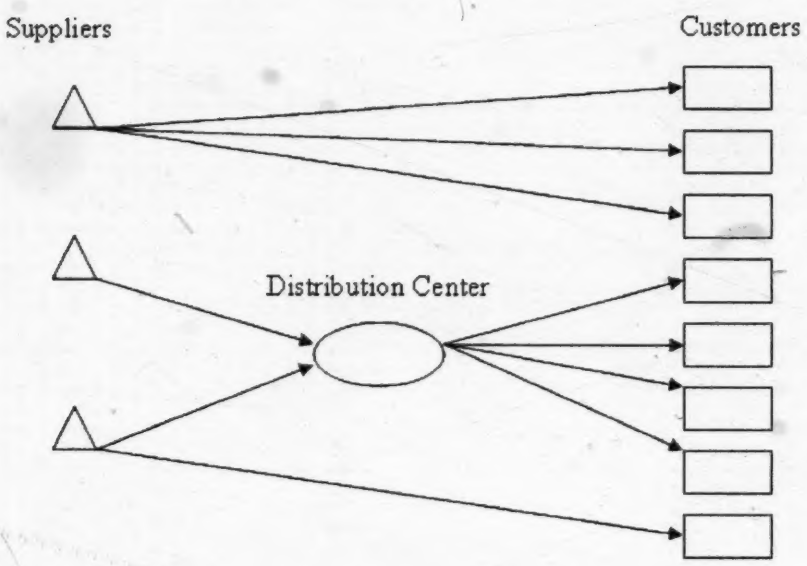

Figure 3-2 Transportation Network

The following transportation-related factors influencing the supply and demand planning have been tracked.

- Average truck size: measures the average load size of each truck.
- Average truck loading preparation time: measures the interval time between trucks arriving.

4. **Baseline inventory level:** In the batch plant, demand is somewhat unpredictable and occurs in a relatively short time prior to production. The production process and distribution process are synchronic; otherwise, the demand will be lost or backlogged. Furthermore, the zero wait modes impose constraints on the exact sequence and timing of the activities. For relaxing these constraints, intermediate inventory has to be stored to reduce lost sales or backlog. On the other hand, as mentioned the unsold inventory cannot be held in the plant for any great length of time.

Two variables, replenishment quantity and baseline quantity, are to be taken into account with respect to inventory management. The replenishment quantity controls order-up-to level, which is held in order to circumvent excessive replenishment costs. The baseline quantity affects the safety inventory levels to avoid backlog (Cheng 1996). Because the production pattern is make-to-order, production does not stop until the customer demand is met in the batch plant supply chain. The replenishment quantity always equals the demand quantity, so that the only issue remaining is to determine the baseline inventory quantity in the face of uncertain demand. Larger values of baseline inventory quantity will result in a lower probability of lost sales but higher average inventory levels. Lower values of baseline inventory quantity, in turn, will result in a higher probability of lost sales but lower average inventory levels.

To find the optimal baseline inventory level, the following assumptions are made:

1. Demand is uncertain.
2. Any orders that cannot be satisfied from stock are considered as lost sales.
3. Replenishment lead times are fixed and known.

The notations used in the mathematical formulas are as follows:

X_t = the inventory level in period t
Q_t = the baseline inventory level in period t
D_t = demand in period t

The function was constructed as follows:

$$D_t = \begin{cases} Q_t - X_t & if Q > X \\ 0 & if Q < X \end{cases} \qquad \text{(Equation 3-4)}$$

At any time t, the inventory level is equal to X_t. If the inventory level X_t is less than Q_t, then the demand quantity is $Q_t - X_t$. If the inventory level X_t is more than Q_t, then no products are to be demanded at time t.

3.3.3 Constraints and Assumptions

The batch plant supply chain template includes the following constraints and assumptions in order to properly represent the real situation.

- *Overtime constraints*: The constraints require that no employee work more than certain hours in each period, as determined by labour laws or company regulations. This requirement limits the total number of overtime hours available.
- *Workforce constraintss*: Constriants of hiring and layoff are required, since they can have a significant negative impact on the morale of the workforce.
- *Production capacity constraints*: In each period, the maximum amount of production cannot exceed the available capacity. This set of constraints limits the total production capacity according to the total internal available capacity.
- *Storage capacity constraints*: The inventory level cannot exceed the available storage capacity.
- *Layout constraints*: Layout constraints limit increases in storage capacity, increases in production facilities, as well as changes to the distribution plan.
- *Constraints from customers*: Customers have special requests for products, such as mix type, distribution date, and pick-up location.

Since the batch plant supply chain is very complex, not every detail dealt with in reality can and should be represented in this simulation model. It is always necessary to abstract from reality in order to manage the batch plant supply chain. The art of model building is to represent reality as simply as possible but as detailed as necessary (Fleischmann et al.

2005). The template holds two assumptions in order to simplify the simulation process, since they have to do with two aspects which are not key factors in the research.

- The raw material supplements in the batch plant are not considered in the template. It is assumed that a plant can have the raw materials required ready in advance of production.
- Since subcontracted production is not included in this template, the available production capacity is limited within the plant.

3.4 Batch Plant Supply Chain Template Modeling Elements

Simphony, a special purpose simulation tool, was used to create the batch plant supply chain template for synchronizing the flow of materials, optimizing the utilization of resources, maximizing the production rate, and reducing inventory levels along the entire supply chain. The template users are required to manually input a value for each parameter in the model elements. The values will be automatically used in the functions included in the elements in order to calculate the outputs. The elements in the batch plant supply chain template are listed in Table 3-1, and are also described in this section.

Table 3-1 Model elements in the batch plant supply chain template

Element	**Description of Parameters**
Parent	Member's name Shift number per day Running hours per shift
Order	Order source (database or statistical distribution) The address for the database file The place where the order comes from Demand statistical distribution
Production	Production rate Switch time for changeover or setup
Storage	Storage ID Capacity of each storage Maximum Level of the inventory Minimum Level of the inventory
Truck Generation	Truck loading preparation time Truck load size
Load/Dump Truck	Load or Dump Rate for the transportation truck
Transportation	Distance between the plants to the distribution centers Transportation speed

3.4.1 Parent Element

The parent element represents a member in the batch plant supply chain, such as plant or distribution center. This element can include all other elements existing within this member: production, storage, truck generation, etc. Three input parameters can be used to define the plant's name and to input the available work hours per day.

- Name: This parameter defines the member's name in the supply chain. For instance, if a user enters the name, "Distribution Center", it will show on the element's icon.
- Shift number: This parameter reflects the daily number of shifts per member, which depends on customer demand and workforce.
- Shift hours: Shift hours are running hours per shift. Shift hours multiplied by shift number will render the maximum available work time.

3.4.2 Order Element

The order element is used to generate the observed customer demand using an historical database or statistical distribution. Once the order element has been created in the model window, the user should choose the data type. As illustrated in Figure 3-3, different property windows are shown once the user chooses the data type. If the data type is database, the user should input the data source which addresses the database file. The historical order data will be directly used as demand input in the model. The output is the order list quoted from the database, such that the user can easily check and change the information. If the data type is statistical distribution, the demand can be randomly generated from six types of statistical distributions (uniform, triangular, normal, constant, exponential, and beta). Each demand may include a maximum of three multiple products. Then the user needs to input the parameters requested in order to define statistical distributions. The element includes six parameters and one output.

The parameters are as follows:

- Data type: Data type is used to define which method—historical database or statistical distribution—is applied in order to generate demand. The historical data has to be imported using the historical database. Otherwise the order is randomly generated by a statistical distribution.
- Data source: if historical database is chosen as the data type, the data source is the address of the database file containing the historical order data.
- From: This parameter indicates where the order comes from.

- Product A: If the data type is statistical distribution, a demand with three multi-products can be generated. Product A, as one of these products, can be randomly generated from the statistical distribution. As mentioned, there are six statistical distribution options: uniform, triangular, normal, constant, exponential, and beta.
- Product B: This is the same as Product A, described above.
- Product C: This is the same as Product A, described above.

The outputs of the element are as follows:

- Order list: This refers to the table storing the historical order data. The order list is quoted directly from the database.

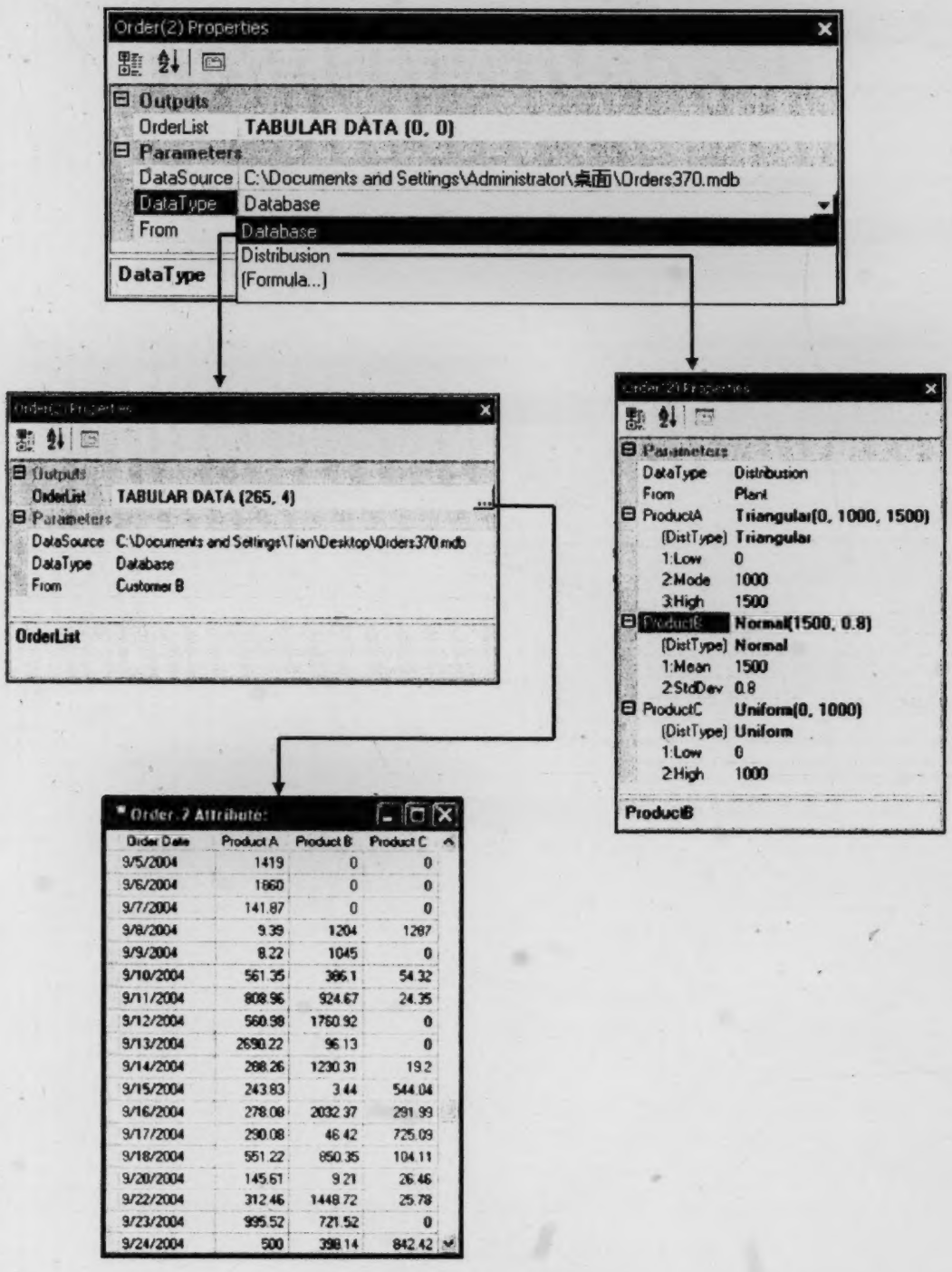

Figure 3-3 Order Element

3.4.3 Production Element

The production element is developed to represent the production task which is to consume resources and time. The resource limitations for the production indicated in the models by *Simphony*'s common template will be introduced at the end of this chapter. The parameters inputted here decide the daily production hours required to meet daily demand.

- Production rate: Production rate is the number of products that can be produced in unit time (such as per hour or per day).
- Switch time: Switch time is the fraction of time for which the facility was unavailable, because it was set up or switched to order to produce different products (unit: minute).

3.4.4 Storage Element

A storage element is developed to represent storage space, which could be a tank or a silo at the batch plant. The number of storage elements in the simulation model represents the number of tanks or silos devoted to the project. The storage capacity is the parameter which decides the maximal volume or weight of each silo or tank. The silos or tanks in the batch plant are also constrained by maximum and minimum level. Combining all of the parameters can help in calculating out the total available storage capacity. If the inventory level is higher than the total available storage capacity, products are oversupplied and production has to be interrupted. Once the inventory level is lower than the minimum level in a silo or tank, the silo or tank needs to be refilled. In a word, the characteristics of batch plant's storage both impact and specify the production process for the batch plant.

- ID: ID is the parameter designed to distinguish the various storage at the same plant.
- Capacity: Capacity is the maximum volume or weight that each silo or tank can hold. Users can define this parameter by any positive number or formula.

- Maximum Level: Maximum level is the maximum amount of inventory that can be stored in a given silo or tank. This is indicated as a percentage of the storage capacity, and is a characteristic of batch plant storage. The maximum level of a silo or tank will be less than or equal to the storage capacity.
- Minimum Level: Minimum level is indicated as a percentage of the storage capacity. This means that once the amount of inventory contained in the silo or tank falls below this level, the silo or tank should be refilled. Again, this is a characteristic of batch plant storage, and the minimum level of a silo or tank will be greater than or equal to zero.

3.4.5 Truck Generation Element

The truck generation element is essential to an accurate representation of the distribution process. This element automatically generates the number of trucks that will be required to transfer product. The number of trucks is based on the quantity of daily demand and the trucks' load size. All trucks coming from external customers or internal distribution centers wait in a queue and load by a FIFO (first in, first out) method. The loading preparation time between each truck also needs to be specified.

- Truck loading preparation time: is the fraction of time between the previous truck transports out of the plant and the next one is ready to be loaded (unit: minute). It could be a positive number defined by users or a random number generated from six different statistical distributions which are uniform, triangular, normal, constant, beta and exponential.
- Truck load size: is a positive number based on the attribute of different kinds of trucks. It decides how many units each truck can load one times.

3.4.6 Load/Dump Truck Element

This element represents the process of loading or dumping trucks. The load or dump rate, which is limited by the characteristics of distribution capability and the truck itself, determines the time consumed by loading or dumping trucks.

- Load or dump rate: This value represents the number of units or tons that can be loaded or dumped in unit time (such as per minute or per hour). Users can define this parameter by means of any positive number or using a formula.

3.4.7 Transportation Element

This element accounts for the activity of transporting products between each member along the batch plant supply chain. The transportation activity could be internal, between the plant and the distribution depot, or external, between the plant and customers. Two factors affect the efficiency of transportation: distance and transportation speed.

- Distance: This is the distance between two members in the batch plant supply chain (units: kilometer).
- Speed: This refers to the speed of trucks transporting the products from one place to another (units: kilometer per hour)

3.5 *Simphony's* Common Template

In order to simulate the batch plant supply chain, a common template in *Simphony* is used in addition to the special purpose template of batch plant, so this section will provide a general introduction to *Simphony*'s common template. Table 3-2 lists the elements used in the model. For additional information about *Simphony's* common template, refer to *Simphony's* general purpose simulation template user guide (AbouRizk 2000).

Table 3-2 Elements in *Simphony*'s Common Template

Elements	**Description**
InPort	Linking between the elements at one hierarchical level and the elements in a lower level
OutPort	Link between the elements in a lower level and the elements at the higher hierarchical level
Conditional Branching	Routing entities into two different braches, true and false, based on a condition associated with the element
Declare Resource	Defining one type of resources in the model in addition to the available number of units
Waiting File	The entities waiting in the file are ranked according to the priority associated with
Capture Resource	Trigger the activity that is capturing requested resources
Request/Release Single Resource	As a child of a capture or release element, this element defines a resource to request or release
Release Resource	Trigger the activity that is releasing requested resources
Create Entities	Creating new entities by the number and time intervals specified and transfer them out
Set Entity Attributes	Assigning values for new or existing attributes of entities
Destroy	Deleting any entities transferred into it
Task	Representing a normal task that requires a duration to perform
Execute	Enforcing the execution of an expression, defining the link property of the input parameter
Consolidate	Managing the number of entities flowing though it
Statistic	Declaring a statistic collected on certain parameters in the model
Statistic Collection	Adding observations to the declared statistical elements

4. Validation of SPS Supply and Demand Planning Template

4.1 Introduction

In Chapter 3, a batch plant supply chain template was developed. The purpose of this chapter is to validate the simulation template. Validation is the process intended to verify that the simulation model is an accurate and reasonable representation of the system. Validation is normally performed in levels involving an examination of data inputs, model elements, subsystems, and interface points (Pritsker and Alan 1989).

Based on this purpose, HKCONSIM (Lu et al. 2003), a computer system for simulation modeling originally developed for Ready Mixed Concrete (RMC) production operations in Hong Kong, was selected as a reference to validate the batch plant supply chain template. The results of HKCONSIM are compared with the outcomes generated by the developed batch plant supply chain template.

This chapter outlines the validation for the batch plant supply chain template. Section 4.2 introduces the Hong Kong concrete industry as a background for describing the HKCONSIM model. Section 4.3 presents the input model. Section 4.4 compares the results of the HKCONSIM model with those of the batch plant supply chain template and explains any pertinent differences. Section 4.5 provides a review of the validation conclusion.

4.2 Project background

The concrete industry in Hong Kong is one of the most intensive in the world. Steady growth of commercial and residential developments will continue to sustain substantial demand for and usage of ready RMC in Hong Kong (Lu et al. 2003).

HKCONSIM, the simulation model, was developed by Ming et al. (2003) for the resource provision planning and production planning of an RMC plant so as to meet daily demands for concrete at a number of sites. Enhancing the coordination between an RMC

plant and the various construction sites is critical to improve the productivity of the placement operation and to enhance the efficiency with which sites and the RMC plant are individually managed (Lu et al. 2003). The objective of the simulation model here is to improve supply service levels and the utilization of plant resources.

4.2 Input Model

The cyclical process of RMC production and delivery between the plant and each site consists of six basic activities (Lu et al. 2003):

1. Batch and load concrete into the truck mixers at the plant (engaging the batch bay);
2. Wash and check the truck mixers at the plant (not engaging the batch bay);
3. Transport the truck mixers to a specified site;
4. Unload the truck mixers on site using a particular placement method (engaging the site crew and equipment);
5. Wash out and wait on site (not engaging site resources); and
6. Return the truck mixers to the plant.

At the plant a FIFO queue is formed which feeds into the task of holding the returning truck mixers waiting to be dispatched for the next delivery.

Figure 4-1 shows the six activities and their inter-relationships. Activities are symbolized with a solid rectangle and their predecessor or successor activities are connected with arrows. The concrete orders received from sites are symbolized with dashed diamonds. The resources used in each activity, such as truck mixers and bays, are inputted into the simulation model. For example, the activity "batch and load" requests an available bay and a free truck mixer.

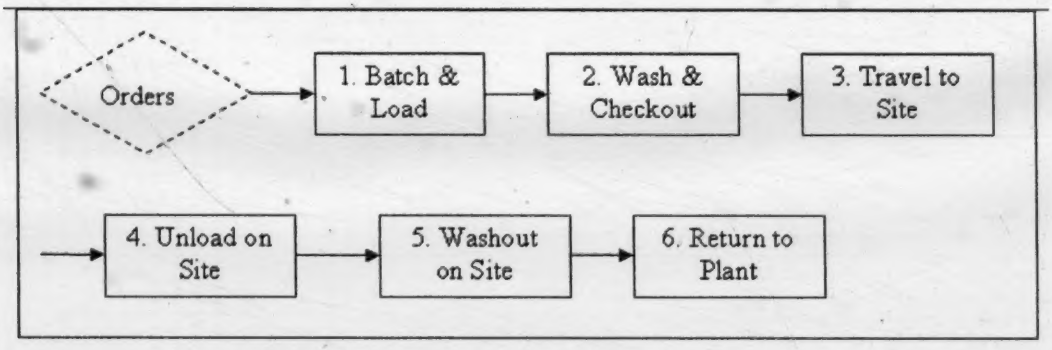

Figure 4-1 The cyclic process of RMC production and delivery

For validating purposes, the simulation model developed by the batch plant supply chain template has the similar input model as the HKCONSIM model. Based on the HKCONSIM model, the parameters of the input model for validation are listed in Table 4-1.

Table 4-1 Parameters of the input model

Activities	Distribution	Par. a	Par. b	Minimum	Mode	Maximum
Batch & Load (5 m^3 truck mixers)	Beta	2.657	4.399	1 min	1.66 min	3 min
Batch & Load (7 m^3 truck mixers)	Beta	2.657	4.399	2 min	2.66 min	4 min
Travel to Site (6-10 km)	Beta	4.248	8.756	6 min	16.04 min	40 min
Unload on Site (5 m^3 truck mixers)	Beta	2.137	6.964	8 min	13.92 min	45 min
Unload on Site (7 m^3 truck mixers)	Beta	3.969	10.914	9 min	20.75 min	60 min
Return to Plant (6-10 km)	Beta	5.471	10.995	3 min	18.76 min	54 min

The model inputs in Table 4-1 are in the form of statistical distributions, which are used in simulation in an attempt to more closely model the actual process. The validation

model built by the batch plant supply chain template uses the data from one day of real operations at a local plant with one batch bay serving 21 pours with 22 truck mixers. The truck mixer fleet consists of 11 trucks with capacities of 5 m^3 and 11 with capacities of 7 m^3. The total order volume to be handled by the fleet is 522 m^3. The simulation results are compared with the outputs of the HKCONSIM model for the purpose of validation.

4.3 Batch Plant Supply Chain Template vs. HKCONSIM

The validation results from the HKCONSIM model—Finish times and resource utilization rates—are compared with the validation model's outputs. The outputs generated by the validation model yield relatively similar results to those of the validated HKCONSIM model. Table 4-2 outlines the outputs from HKCONSIM and the validation model. The differences between the two are also listed in the table.

Table 4-2 Batch plant supply chain model vs. HKCONSIM

Description	Validation Model	HKCONSIM	Difference (%)
End-of-day Finish Time (min)	631	680	7.23%
Plant Resources Utilization Rate (%)	39.44%	36.67%	7.55%
Truck mixers Utilization Rate (%)	66.81%	62%	6.75%

End-of-day finish time is the total working time from the arrival of the first truck mixer at the concrete plant to the return of the last truck mixer from the site. There is 7.23% difference between the output of the validation model built by batch plant supply chain template and the results of the HKCONSIM. The rate of resource utilization at the plant is the fraction of time for which a bay is productive over the total working time. The difference between the two models' outputs here was 7.55%. Truck mixer utilization rate is the fraction of time for which a truck mixer is productive over the total working time. There is 6.75% difference between the validation model and HKCONSIM. These

differences can be attributed to an assumption made for the purpose of simplifying the validation model, which assumes that pump is the only means of unloading the truck mixers (rather than the other five methods). Table 4-3 (Lu et al. 2003) outlines the statistical distributions for the six methods of unloading truck mixers in HKCONSIM. In simplifying the validation process, only one method of unloading truck mixers—a pump method—is used in the validation model.

Table 4-3 HKCONSIM input model for unloading truck mixers

Placing method	Truck volume	Par. a	Par. b	Minimum	Mode	Maximum
Backhoe	5	1.481	1.593	9	14.37	21
Backhoe	7	0.996	3.298	9	8.93	46
Direct tip	5	4.390	9.567	3	8.10	21
Direct tip	7	3.012	3.686	3	10.71	21
Hoist & barrow	5	1.915	4.593	12	22.96	66
Hoist & barrow	7	5.252	9.118	37	46.97	66
Pump	5	2.137	6.964	8	13.92	45
Pump	7	3.969	10.914	9	20.75	60
Crane & 2 skips	5	3.249	9.984	8	18.41	60
Crane & 2 skips	7	3.716	10.891	7	25.31	92
Crane & 1 skip	5	1.584	4.446	9	16.83	63
Crane & 1 skip	7	5.797	11.009	9	31.36	78

4.4 Conclusion

This chapter chooses a model from the literature (HKCONSIM) as a reference by which to validate the batch plant supply chain template. A validation model for RMC production operations was created using the batch plant supply chain template. Comparing the output generated by HKCONSIM versus the validation model shows that the results are relatively close. This means that the batch plant supply chain template is valid. The validated template provides both researchers and industry practitioners with a tool that enables them to perform sensitivity analysis and accounts for alternative scenarios.

5. Case Study

5.1 Introduction

Asphalt production operations can be considered as a typical batch plant supply chain consisting of demand, production, inventory, and distribution processes. A varying and uncertain demand pattern makes the design of a coordination and integration plan in the asphalt plant a challenging task. In this chapter, an existing asphalt plant is presented as a case study in which to apply the batch plant supply chain template to reconfigure and optimize inventory, production, and distribution processes.

The simulation model is built by using the batch plant supply chain template in order to meet variations in the demand pattern of this plant. The model utilizes actual order data in 2004. The model simulates the demand on a daily basis and responses to the demand under different production rates and inventory capacities.

Section 5.2 introduces a typical production process for a hot mix asphalt plant. Section 5.3 describes the problems faced in an asphalt plant to be resolved by means of the simulation model. Section 5.4 outlines the processes of data collection and analysis. Section 5.5 details the process of building the simulation model. Section 5.6 discusses the results of the conducted sensitivity analysis from the simulation model. Section 5.7 developes a linear programming model for the same case and compares the outputs with simulation model.

5.2 Asphalt Plant Case Study

In this section, the typical production process for a hot mix asphalt plant will be introduced as the background for the simulation model. The purpose of an asphalt plant is to blend aggregate and asphalt cement together at an elevated temperature in order to produce a homogeneous asphalt paving mixture. There are two basic types of hot mix asphalt plants currently in use: batch and drum-mix. Both types of plants serve the same ultimate purpose and have similar operations and flow of materials. This section will

refer to a drum-mix plant as an example representing the operation process for hot mix asphalt.

The drum-mix plant consists of five major components: cold-feed system, asphalt cement supply system, drum mixer, surge or storage silos, and emission-control equipment. A typical drum-mix plant is shown in Figure 5-1.

The cold-feed bins are used to proportion the material to the plant. A variable-speed feeder belt is used under each bin. The amount of aggregate drawn from each bin can thus be controlled by both the size of the gate opening and the speed of the feeder belt in order to ensure accurate delivery of the different-sized materials. The aggregate on each feeder belt is deposited onto a gathering conveyor that runs beneath all of the cold-feed bins. The combined material is normally passed through a scalping screen and then transferred to a charging conveyor for transport to the drum mixer (National Asphalt Pavement Association 2002).

The charging conveyor is equipped with two devices using to determine the amount of aggregate being delivered to the plant: a weigh bridge under the conveyor belt measures the weight of the aggregate passing over it, and a sensor determines the speed of the belt. These two values are used to compute the wet weight of aggregate, in tons per hour, entering the drum mixer. The plant computer, with the amount of moisture in the aggregate provided as an input value, converts the wet weight to dry weight in order to determine the correct amount of asphalt cement needed in the mix.

The burner is located at the upper end of the drum. The aggregate enters the drum and is moved down by a combination of gravity and the configuration of the flights. The asphalt cement is pulled from the storage tank by a pump and fed through a meter. The binder material is then delivered through a pipe into the rear of the mixing drum, where the asphalt cement is injected onto the aggregate (National Asphalt Pavement Association 2002).

Coating of the aggregate occurs as the materials are tumbled together and moved to the discharge end of the drum. The asphalt mix is deposited into a conveying device for transport to a storage silo. The silo converts the continuous flow of mix into a batch flow for discharge into the haul vehicle (National Asphalt Pavement Association 2002).

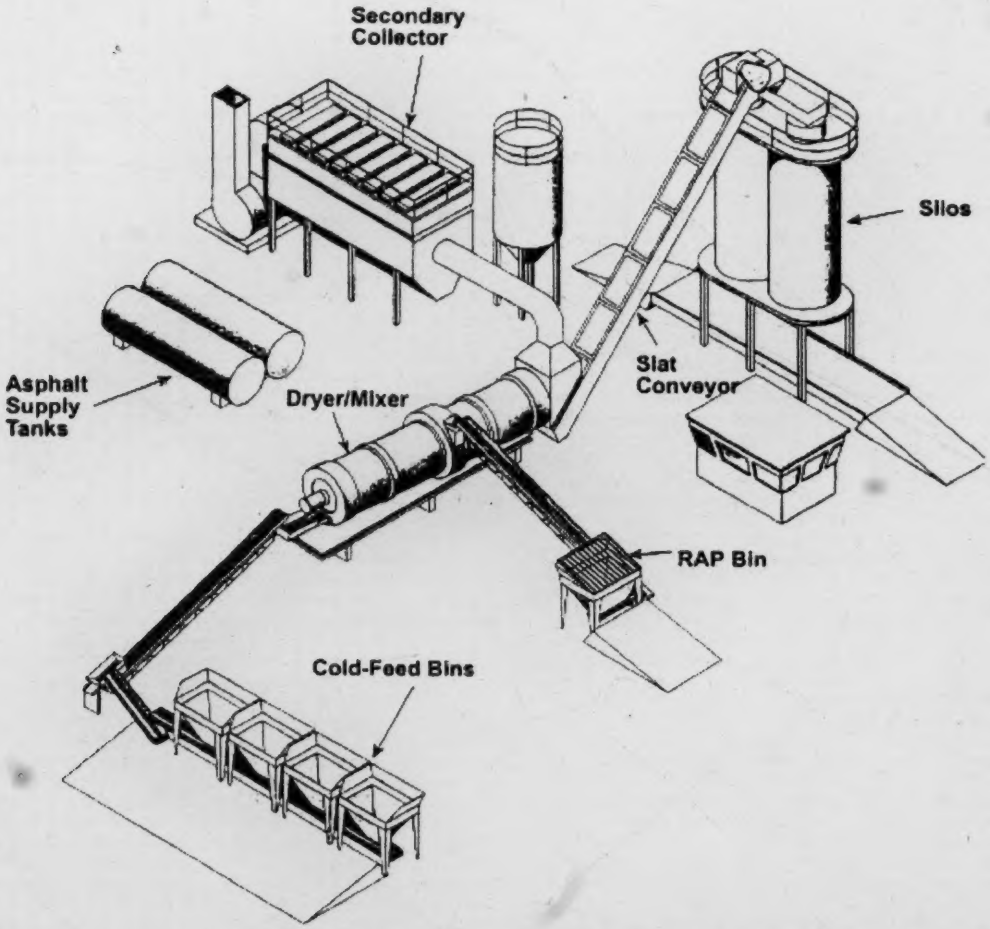

Figure 5-1 Major components of a drum-mix asphalt plant
(National Asphalt Pavement Association, 2002)

5.3 Problem Description

Lafarge, a major asphalt producer, has two plants in Calgary—one in the North of the city (Spyhill Asphalt Plant) and one in the South (Bow River Asphalt Plant). A recent financial study shows the potential savings of changing the operation plan. The proposed operation plan includes eliminating the south plant and changing it to a transfer depot in order to release some of the capital invested there and utilizing the north plant, located near to the aggregate pits, to its full capacity. The purpose of developing the model is to simulate the new scenarios to result from the conversion of the south plant to a depot. The model assumes that customer demand and storage capacity in the south depot will be the same as in the south plant. The outputs of the model will support the decision making process.

The asphalt plant consists of four main processes—demand, production, storage and distribution—which are described here:

- *Demand*: The number of customers varies in different seasons. Usually there are 2 to 4 external customers and 3 internal paving crews placing orders for asphalt. Depending on the proximity of the jobsite, the customers may prefer to place their orders to either the north plant or the south depot. The customers operate their own trucks to transport asphalt from the plant or depot to the jobsite. Both the plant's customers and the depot's customers place their orders one day ahead of when they want the products. Orders from the north plant have a higher priority. After the last order from the north plant, Spyhill, has been fulfilled, production of asphalt for the south depot commences.
- *Production*: According to the proposed plan, the north plant currently maintains a production rate of 300 tons/hour. Different mixtures can be produced based on a customer's demand, but switching the production from one mixture to another takes an average of half an hour. The north plant runs two working shifts, from 6 AM-2 PM and from 2 PM-10 PM.

- *Storage*: All types of finished mixtures are stored in silos which can hold the mix for up to 72 hours. Silos come with varied storage capacities but all silos within any given plant should have the same capacity. The number of silos can vary while being limited by the plant's site layout. A silo cannot be filled to more than 90% of its capacity. As soon as a silo emptied, it needs to be refilled unless the demand has been met. The silo cannot be filled while it is occupied with truck loading operations.
- *Distribution*: Trucks begin arriving at the Spyhill plant starting at 7 AM and are served in a FIFO (first in, first out) method. After the last order from the north plant has been distributed, the transferring of asphalt to the south depot begins. Because this transferring between the plant and the depot occupies the plant's trucks, it has to be taken into account.

The challenge here is the lack of a quantitative assessment of the new plan. Whether or not the plant and the depot will be able to meet all of the demand previously handled by two plants is a significant problem facing decision makers. In addition, whether or not the extra productivity and extra storage capacity are actually needed is another issue to be addressed. How to minimize the inventory level as well meet the orders is another challenge for this project. The goal of this study is to model the new operation plan using simulation in order to evaluate the effects of these factors.

5.4 Data Collection and Analysis

Under a well controlled asphalt plant, historical orders are usually available. A complete database will help to generate more accurate results through the use of a simulation model. The database used in the simulation model collects the truck load records dated from January, 2004 through to December, 2004 from the North site (Spyhill Asphalt Plant) as well as the South (Bow River Asphalt Plant). Utilizing real data collection is an important advantage of this modeling.

Table 5-1 shows the original database information from Lafarge. The plant ID for Spyhill plant is 370 and the ID for Bow River plant is 371. The order code is the identification

number for different orders. The date and time for every load is also recorded in the database. Product ID and mix type distinguish between different kinds of products demanded by customers. Load size reflects how many tons of asphalt is transfered out from the plant at a given time. Customer name and customer number distinguish between customers.

In order to generate the order information, any relevant data is filtered out and sorted as shown in Tables 5-2 and 5-3. Table 5-2 shows the order data from the Spyhill plant and Table 5-3 represents the order data from the Bow River plant. Truck loading records are sorted according to the different kinds of mix types so that load sizes are added together to obtain the order for each day.

To simplify the order data, the first three maximum orders are selected as prime orders regardless of how many types of mix are actually ordered in a given day. If there are less than three types of mix ordered in one day, the value should be zero. Tables 5-4 and 5-5 show the final order databases inputted into the simulation model.

Table 5-1 Database of truck loading records

Plant ID	Order Code	Date Load	Time Load	Product ID	Mix Type	Load Size	Customer Number	Customer Name
370	37001	2004-1-6	1:22:28 PM	8841	Mix A	13.18	216234	LCM
370	37001	2004-1-6	1:32:45 PM	8841	Mix A	14.51	216234	LCM
370	37001	2004-1-6	1:35:24 PM	8841	Mix A	12.28	216234	LCM
370	370002	2004-1-6	2:28:46 PM	8675	Cold mix	8.96	882372	MACO
370	37002	2004-1-6	2:32:25 PM	8675	Cold mix	9.58	882372	MACO
370	37014	2004-1-9	12:11:34PM	8650	16MM	14.20	882372	MACO
371	37101	2004-1-5	12:15:31PM	8841	Mix A	9.04	234267	METRO
371	37102	2004-1-5	1:20:45 PM	8660	Mix B	12.21	234267	METRO
371	31003	2004-1-5	1:50:23 PM	7770	MSM	10.11	234267	METRO
371	37104	2004-1-7	2:48:41 PM	7770	MSM	11.21	216234	LCM
371	37104	2004-1-7	2:54:46 PM	7770	MSM	13.31	216234	LCM

Table 5-2 Order records for Spyhill plant

Date	Mix Type	Order
2004-1-6	Mix A	39.97
2004-1-6	Cold mix	18.54
2004-1-9	16MM	14.20

Table 5-3 Order records for Bow River plant

Date	Mix type	Order
2004-1-5	Mix A	9.04
2004-1-5	Mix B	12.21
2004-1-5	MSM	10.11
2004-1-7	MSM	24.52

Table 5-4 Order database for the Spyhill plant

Data	First Prime Order	Second Prime Order	Third Prime Order
2004-1-5	0	0	0
2004-1-6	39.97	18.54	0
2004-1-7	0	0	0
2004-1-8	0	0	0
2004-1-9	14.20	0	0

Table 5-5 Order database for the Bow River plant

Data	First Prime Order	Second Prime Order	Third Prime Order
2004-1-5	1221	10.11	9.04
2004-1-6	0	0	0
2004-1-7	24.52	0	0
2004-1-8	0	0	0
2004-1-9	0	0	0

Figure 5-2 shows the cumulative density function (CDF) of order quantity from the Spyhill plant. The three curves in the figure illustrate the three prime orders for each day. The unit for the order quantity (on the X-axis) is the ton. The Y-axis represents the percentage by which the order quantity is below that observation. For example, as can be seen in Figure 5-2, the second prime order in each day has a 90% probability under 1000 tons.

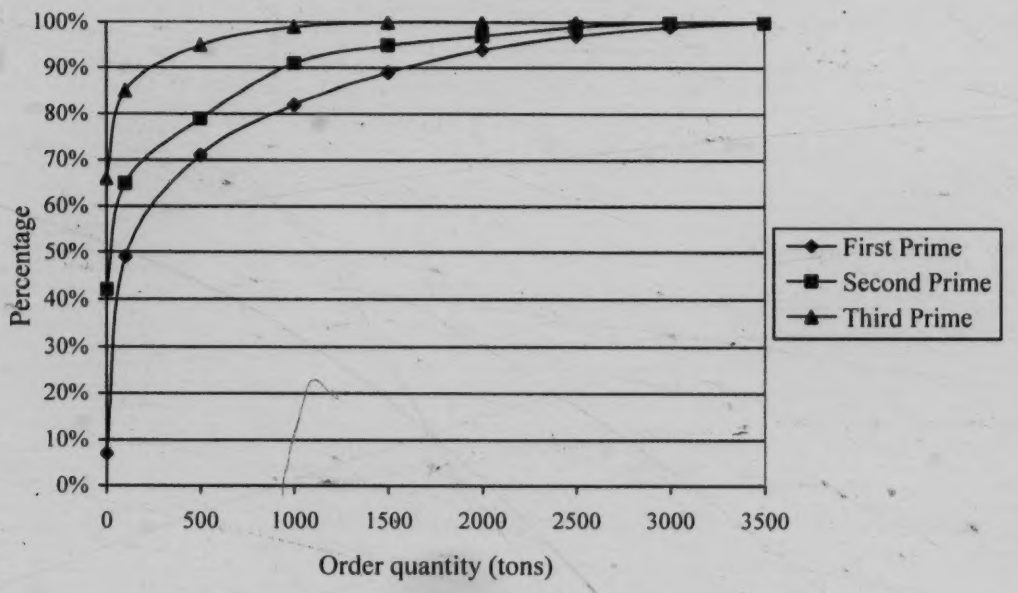

Figure 5-2 Order quantity CDF for the North plant

Figure 5-3 shows the CDF of order quantity from the Bow River plant. The three curves in the figure illustrate the three prime orders for each day. The unit used for the order quantity (X-axis) is the ton. Here again the Y-axis represents the percentage by which the order quantity is below that observation. For example, as can be seen in Figure 5-3, the first prime order for each day has a 90% probability under 1200 tons.

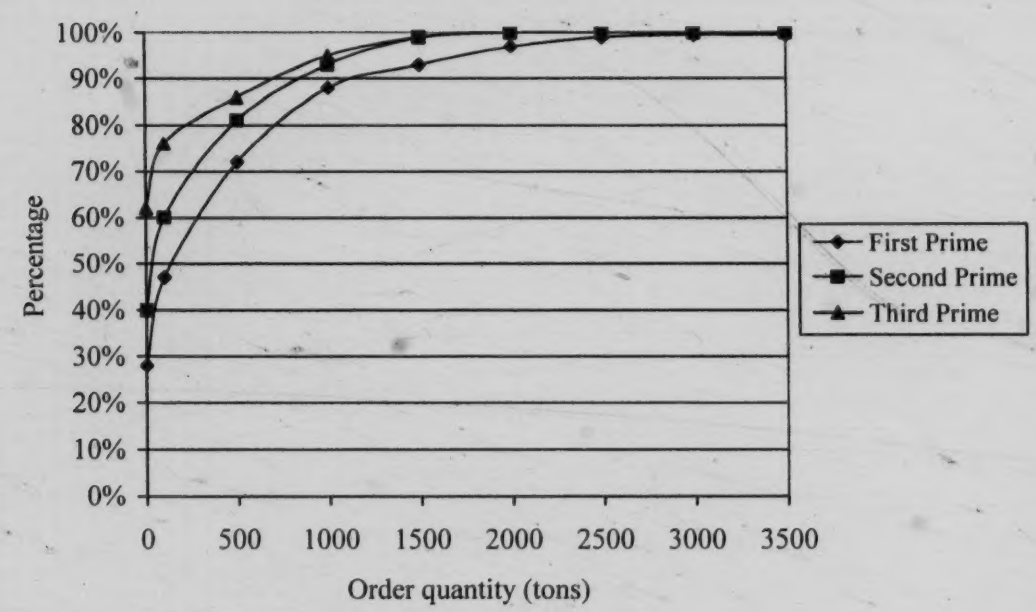

Figure 5-3 Order quantity CDF for south plant

5.5 Simulation Model Building

In the section, the process of model building will be described. Figure 5-4 shows the process map.

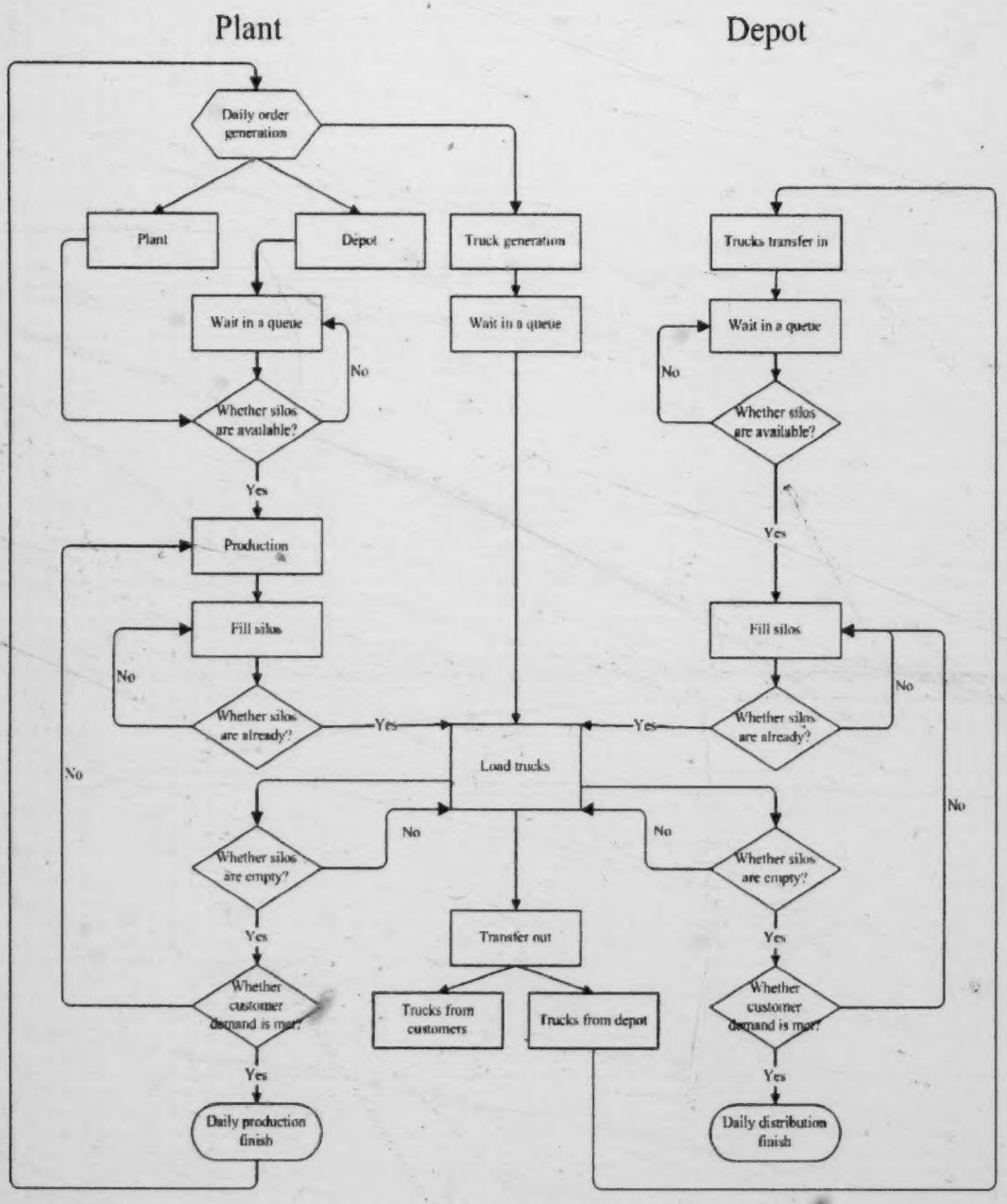

Figure 5-4 Modeling Process

The model starts by generating orders from both the North plant and South depot. Two methods are available in the batch plant supply chain template (described in detail in Chapter 3), which are randomly generated from the distributions (constant, uniform,

triangular, normal, exponential, and beta) or are read from the historical database. In this case study, the historical database from 2004 was inputted into the model. The orders from the North plant, as mentioned, have a higher priority than those from the South depot. The orders not yet produced wait in a queue to be processed based on their priority.

It will take some time to produce the orders, depending on the production rate and the switch time for changing over the different mixtures. The machine resource is captured during the production process. Then the mix is to be filled in an available silo, which is also captured as resource. If all of the silos are full, meaning that no more storage is available, the production will be interrupted.

Different mixtures are stored in different silos. The number of silos and the capacity of each silo are claimed and defined as input in the model. Once the silo is ready, trucks come into the plant and load asphalt. Needless to say, silos cannot be filled more than their maximum level. Furthermore, the loading of trucks and the filling of silos cannot occur simultaneously. All this means that if trucks load asphalt under a particular silo, that silo cannot be filled or refilled at that time. Once the silo is emptied, and if customers' demands have not yet been satisfied, the silo can be refilled. The number of bays in the asphalt plant needs to be defined in the simulation model, which determines the number of trucks that can be loaded at the same time.

Trucks coming from customers or from the South depot are assumed to be ready at any time. The users can define any of three different load sizes as input parameters. The model will automatically generate enough trucks to handle daily orders from both the North plant and the South depot. According to the loading preparation time between trucks, trucks load the asphalt one by one.

If orders are demanded by the customer from the North plant, the external trucks of the customers distribute the mixture out of the plant. Beyond distributing out the mixture, all activities here exceed the scope of this research. If orders are placed for the South depot,

the company's trucks transport the mixture to the depot. Then the simulation model includes the activities occurring there.

Trucks transport the asphalt from the North plant to the South depot. The depot's silos are then filled. The number of silos and the capacity of each silo are claimed and defined as input in the model, just as for the Plant. The number of bays in the depot also needs to be inputted. The dumping rate of the trucks determines the silos' filling speed. Once any one of silos in the depot is ready to load trucks, the model will automatically generate enough customers' trucks to transport the asphalt out of the depot. Beyond transferring out the mixture, all other activities are outside the scope of this research.

There are three parts comprising the first level in the simulation model: plant, transfer, and depot (Figure 5-5). The arrow directs the way the products flow among the members in the supply chain. Figure 5-6 shows the child window under the "Plant" element. Figure 5-7 shows the child window under the parent element "Depot".

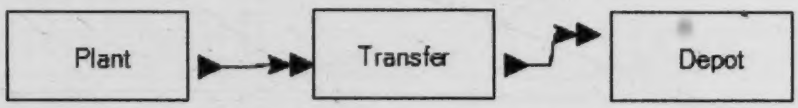

Figure 5-5 First level of the Lafarge project

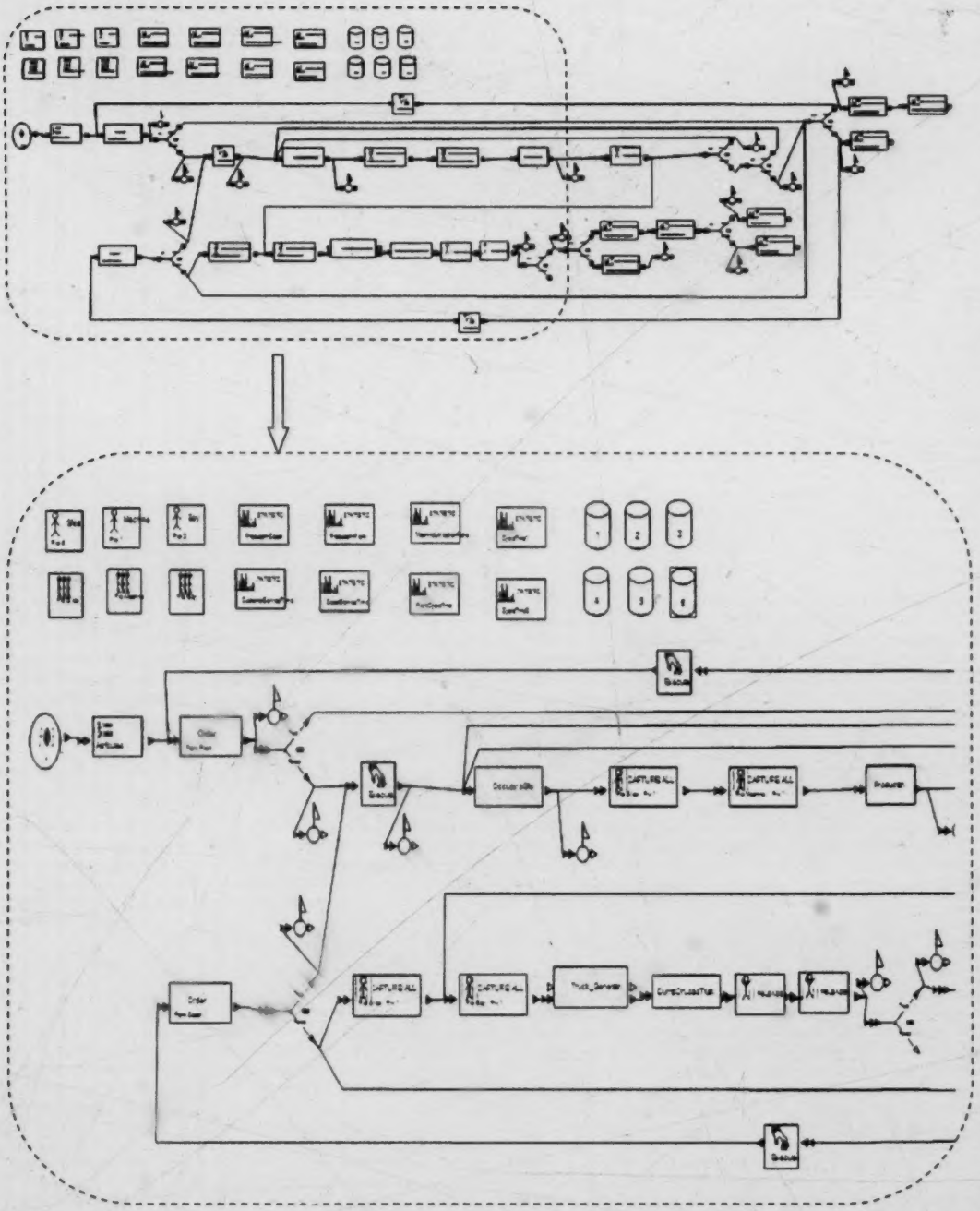

Figure 5-6-1The child window inside the plant element

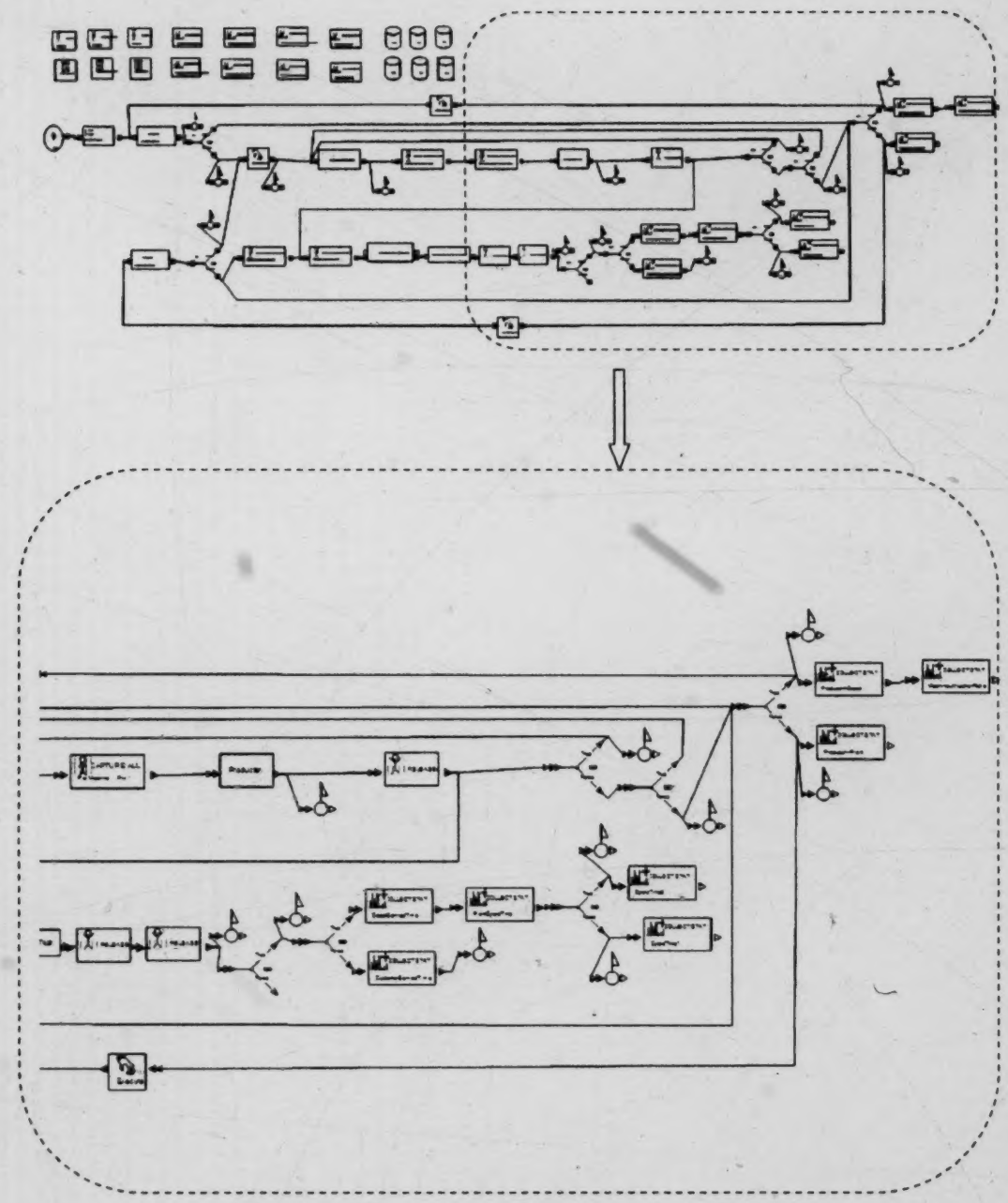

Figure 5-7-2 The child window inside the plant element

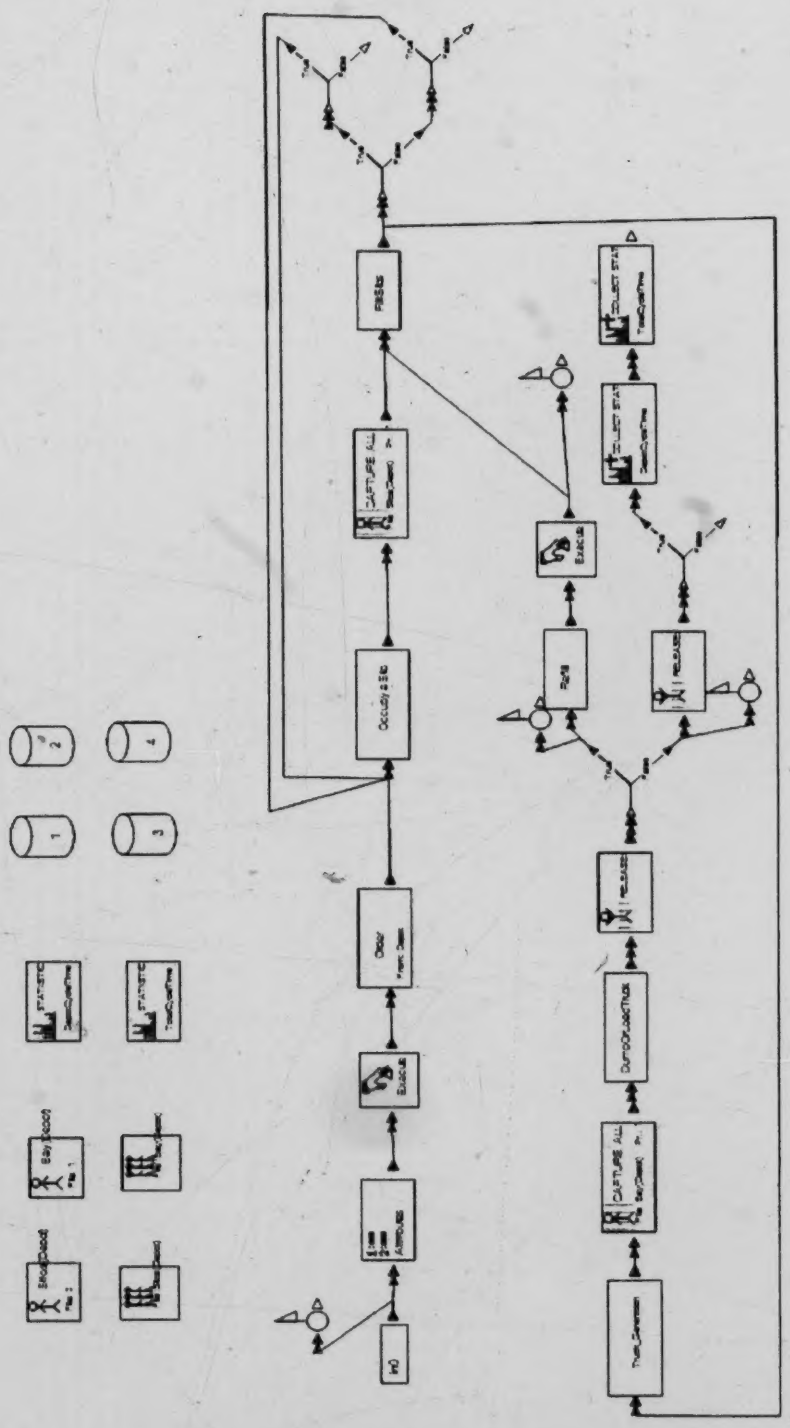

Figure 5-8 The child window inside the depot element

5.6 Sensitivity Analysis

After developing the simulation model for the asphalt plant project, a sensitivity analysis was performed in order to determine what factors affect the production capacity of the asphalt plant and also to quantify the effect of each of those factors. This sensitivity analysis was performed by changing the model attributes and running the simulation model.

5.6.1 Intermediate Storage Capacity

The first two investigated factors affecting intermediate storage capacity are the capacity of the silos and the number of silos. The assumed properties for the sensitivity analysis are shown in Table 5-6. In conducting the sensitivity analysis, five curves represent five different silo capacities, as shown in Figure 5-8.

Table 5-6 Model properties for intermediate storage capacity sensitivity analysis

Bays	Truck Loading Preparation Time (min.)	Load/Dump Rate of Trucks (tons/min.)	Production rate (tons/hr.)	Switch Time (min.)
2	3	3	300	30

As shown in Figure 5-8, reducing the number of silos can increase the plant's work hours. In theory, the plant's work hours increase obviously as the number of silos approaches zero. This means that without intermediate storage, production process is hard to be synchronic with distribution process. On the other hand, with the number of silos increasing, the work hours eventually reach a constant value. This is the expected behavior of the work hours as a function of intermediate storage capacity in the asphalt plant. In other words, intermediate storage capacity is on the threshold of an unaffected factor of work hours, once the number of silos exceeds six.

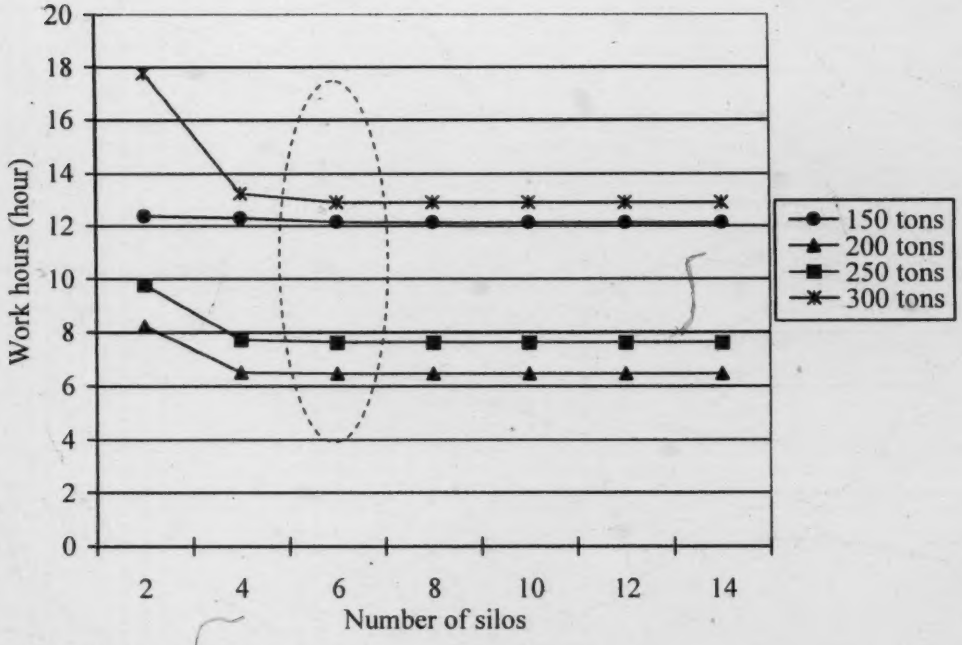

Figure 5-9 Intermediate storage capacity vs. work hours (average)

In comparing the four alternatives, for the same silo number with capacities ranging from 150 to 300 tons, it shows that using 300-ton silos leads to maximum work hours; meanwhile, using 200-ton silos results in minimum work hours. The explanation for this result is that as the silo's capacity becomes smaller, the capacity of the storage is not sufficient to ensure the machine's productivity so that machine has to wait to work while the intermediate storage is full. On the other hand, the larger the capacity of each silo becomes, the longer trucks will have to wait to be loaded since the loading of trucks and filling of silos cannot be performed simultaneously for a given silo. As the main parameter determining a plant's work hours, the optimum silo capacity is a certain solution which results in minimal work hours. The result shows that 200 tons is the most suitable silo capacity coordinating and integrating with other factors along the batch plant supply chain. With respect to the four different silo capacities ranging from 150 to 300 tons (Figure 5-8), the relationship between silo capacity and plant work hours with the number of silos set at six can be seen clearly in Figure 5-9.

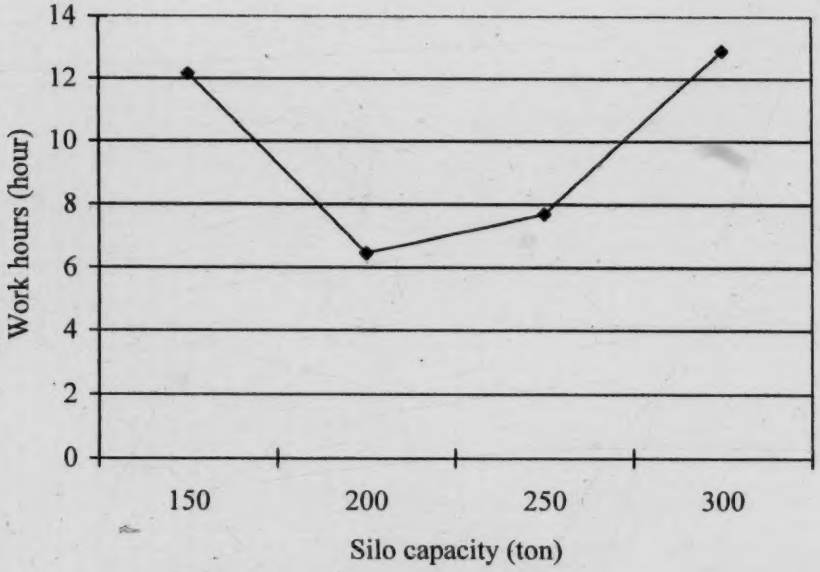

Figure 5-10 The relationship between work hours and silo capacity

All work hours generated by the simulation model with different intermediate storage capacities are presented in Table 5-7. The underlined values in the table correspond to the thresholds at which increasing the number of silos will not affect the plant's work hours. These values are crucial to deciding the necessary number of silos needed in the North plant at varying capacities.

Table 5-7 Intermediate inventory capacity vs. work hours (average)

Number of Silos	Silo Capacity (ton)			
	150	200	250	300
2	12.37	8.22	9.78	17.78
4	12.31	6.5	7.72	13.23
6	12.15	6.46	7.69	12.89
8	12.13	6.46	7.62	12.89
10	12.13	6.46	7.62	12.89
12	12.13	6.46	7.62	12.89
14	12.13	6.46	7.62	12.89

5.6.2 Production rate

The next variables to be considered for the sensitivity analysis which can affect work hours in the plant are production rate and switch time of facilities. The assumed properties for the sensitivity analysis are showing in Table 5-8. In conducting the sensitivity analysis, four different curves represent different switch times in Figure 5-10.

Table 5-8 Model properties for production rate sensitivity analysis

Bays	Truck Loading preparation Time (min.)	Load/Dump Rate Of Trucks (tons/min.)	Silo Capacity (ton)	Number of Silos
2	3	3	200	6

The proposed plan includes eliminating the South plant by converting it to a transfer depot and utilizing the north plant to its full capacity. This implies that determining whether or not the North plant's production rate is sufficient to meet customer demand is the most important challenge involved in the change. Accordingly, a sensitivity analysis is required to investigate the benefits of increasing the production rate by reducing work hours to meet customer demand.

The plant's work hours as a function of the production rate exhibit an expected behavior. In decreasing the production rate, as the rate approaches zero, the plant's work hours approach infinity, meaning that production cannot be accomplished with a zero production rate. Meanwhile, with the production rate increasing, the plant's work hours will obviously reduce. However, after the production rate exceeds 300 tons per hour, the work hours reach a constant value which is close to the value associated with an infinity production rate. The explanation of this occurrence is that work hours consist of two parts in the North asphalt plant—production time and distribution time. The plant's work hours approach a value which equals the value of distribution hours as the production rate approaches infinity.

Four alternative switch times ranging from 10 to 40 minutes were compared. As can be expected, the shorter the switch time is, the fewer the plant work hours are. On the other hand, of course, since no more than three types of asphalt mixtures are used in a given day, switch time is not a particularly sensitive determinant of work hours.

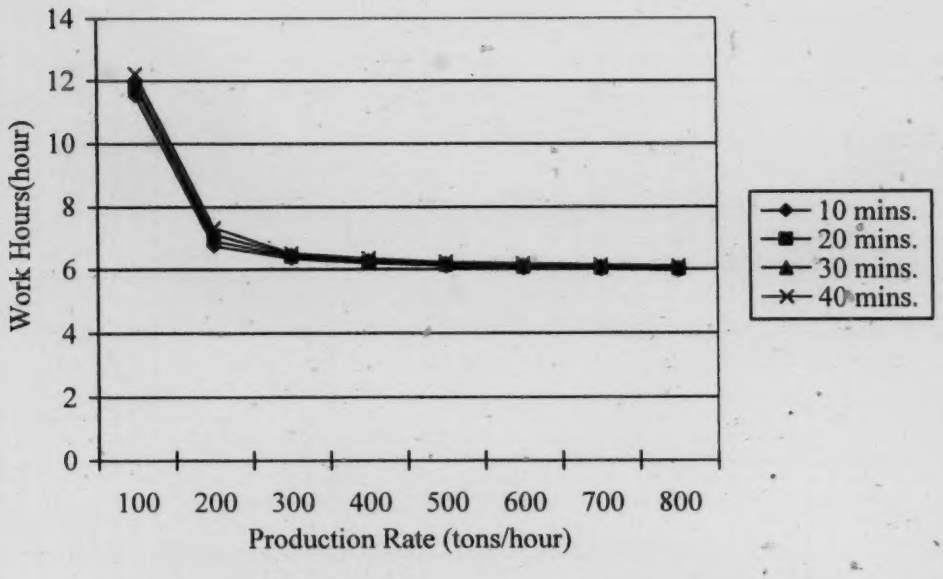

Figure 5-11 Production rate vs. work hours (average)

All work hours generated by the simulation model with varying production rates and switch times are presented in Table 5-9. The work hours in the table decreases less and less as production rate increases. These values are important to deciding on a necessary and economical production rate for the North plant.

Table 5-9 Production rate vs. work hours (average)

Production rate (tons/hr)	Switch Time (minutes)			
	10	20	30	40
100	11.52	11.78	11.98	12.22
200	6.74	6.91	7.11	7.33
300	6.35	6.4	6..46	6.51
400	6.19	6.23	6.28	6.35
500	6.10	6.14	6.19	6.24
600	6.04	6.08	6.13	6.18
700	6	6.04	6.09	6.14
800	5.97	6.01	6.05	6.10

5.6.3 Distribution Capacity

The next variables to be considered for sensitivity analysis in this study are tied to the distribution plan, which is concerned with truck loading preparation time and the number of bays. Number of bays reflects the number of trucks that can be loaded simultaneously. The distribution capacity of the plant depends on these two factors. The assumed properties for the sensitivity analysis are shown in Table 5-10. In conducting the sensitivity analysis, the three different curves represent different numbers of bays (Figure 5-10).

Table 5-10 Model Properties for distribution capacity sensitivity analysis

Production rate (tons/hr.)	Switch Time (min.)	Load/Dump Rate Of Trucks (tons/min.)	Silo Capacity (ton)	Number of Silos
300	30	3	200	6

The plant's work hours as a function of the distribution capacity exhibit an expected behavior. In decreasing the truck loading preparation time to zero, the plant's work hours approach a fixed value which is the time with all trucks standing by. On the other hand, increasing the truck loading preparation time can obviously increase the plant's work

hours. Comparing the three curves, one will observe that the more bays exist in the plant, the more trucks can be loaded at the same time, and the fewer work hours will be required. This factor is extremely sensitive with respect to a plant's work hours when the number of bays changes from one to two. However, the number of bays is constrained by several inflexible factors such as the number of silos and the site layout of the plant.

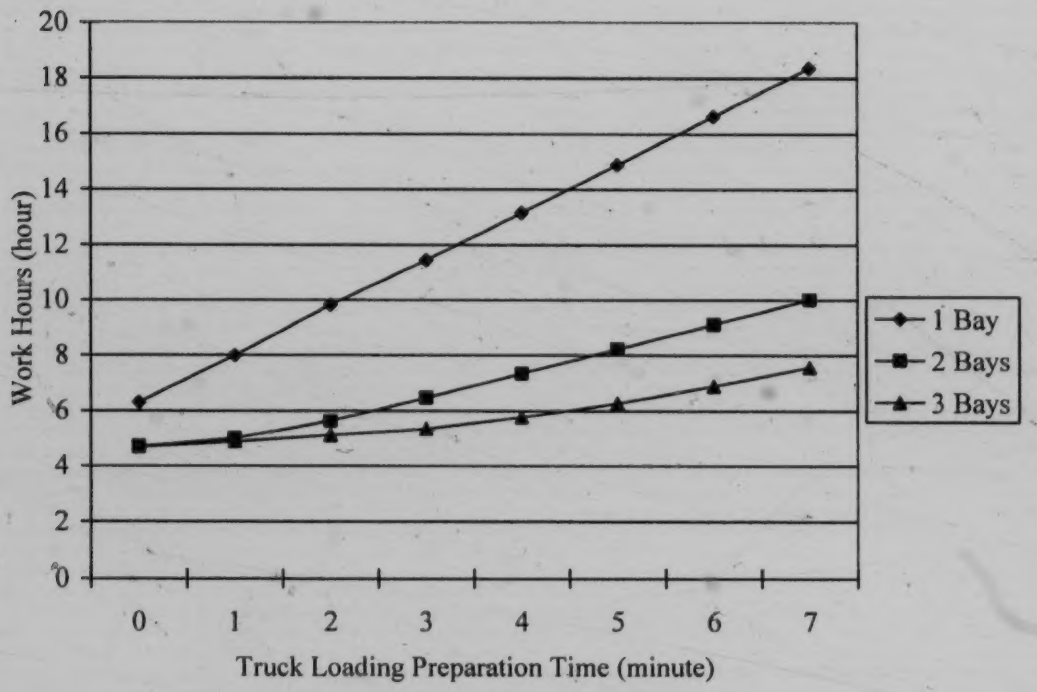

Figure 5-12 Distribution capacity vs. work hours (average)

The work hours generated by the simulation model for different truck loading preparation times and different numbers of bays are shown in Table 5-11. Based upon the values in the table, both the number of bays and the truck loading preparation time are sensitive factors for the plant's work hours. These values are influential in determining the distribution plan and the North plant site layout that will best serve to meet customer demand following the conversion of the plant.

Table 5-11 Distribution capacity vs. work hours (average)

Truck Loading Preparation Time (minute)	Number of Bays		
	1	2	3
0	6.30	4.72	4.70
1	7.99	5.01	4.89
2	9.82	5.63	5.12
3	11.43	6.46	5.35
4	13.16	7.34	5.77
5	14.89	8.23	6.27
6	16.62	9.12	6.89
7	18.35	10.01	7.56

5.6.4 Service Level

The fourth variable to be considered for the sensitivity analysis is service level. The service level is the percentage of demand completed on time and in full capacity. The assumed properties for the sensitivity analysis are shown in Table 5-12.

Table 5-12 Model properties for service level sensitivity analysis

Bays	Silo Capacity (ton)	Number of Silos	Truck Loading Preparation Time (min.)	Load/Dump Rate Of Trucks (tons/min.)	Production rate (tons/hr.)	Switch Time (min.)
2	200	6	3	3	300	30

For the sensitivity analysis, the curve represents the change in service level corresponding to an increase in demand (Figure 5-12). The inputted demand in the simulation model is derived from the historical order data from 2004. Based on these orders, the demand is increased from 0% to 20%. As can be seen in Figure 5-12, if the demand keeps stand with the historical data, changing the South plant to a transfer depot and only utilizing the north plant for produce can result in meeting 95.47% of customer

demand. If the demand increases up to 10%, Figure 5-12 shows that the service level will decrease to 83.85%. The service level decreases to 61.13% once the demand increases over 20%. This means that the facilities and capacity of the North plant fail to satisfy customer demand. New machinery and/or more storage space should be invested in accordingly for the North plant.

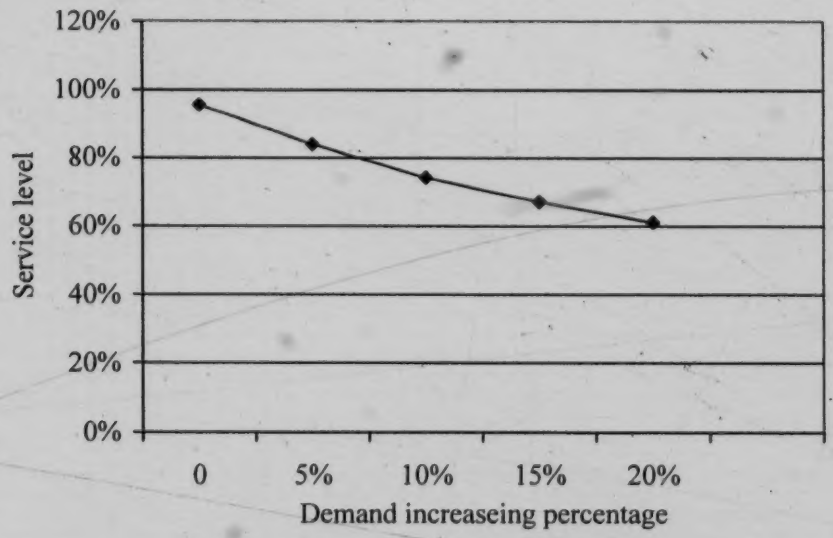

Figure 5-13 Service level vs. demand increasing percentage

The service levels corresponding to different percentages of demand are shown in Table 5-13. These values are important for managing and controlling the demand from customers and forecasting future investments in new facilities.

Table 5-13 Increasing percentage of demand vs. service level

Increased percentage of demand (percentage)	Service level (percentage)
+0%	95.47%
+5%	83.85%
+10%	74.13%
+15%	67.2%
+20%	61.13%

5.6.5 Baseline Inventory Level

The last variable to be considered for the sensitivity analysis is baseline inventory level. Inventory is used to reduce lost sales despite uncertainty of demand. Lost sales are the percentage of demand not completed on time and in full. This section analyzes the percentage of lost sales corresponding to different baseline inventory levels as demand increases. The inputted demand in the simulation model is the historical order data from 2004. Based on these orders, the demand is increased from 0% to 20%. The assumed properties for the sensitivity analysis are shown in Table 5-14. Five different curves represent the varying percentages of increasing demand (Figure 5-13).

Table 5-14 Model properties for inventory level sensitivity analysis

Bays	Silo Capacity (ton)	Number of Silo	Truck Loading Preparation Time (min.)	Load/Dump Rate Of Trucks (tons/min.)	Production rate (tons/hr.)	Switch Time (min)
2	200	6	0	3	300	30

As shown in Figure 5-13, increasing the inventory level can decrease the percentage of lost sales. And as can be expected, the percentage of lost sales approaches a maximum level as the baseline inventory level approaches zero. The maximum percentage is the percentage of lost sales without inventory. Alternatively, as the inventory level increases, the percentage of lost sales approaches a constant value. This is an expected occurrence which can be explained by the fact that lost sales depend on two constraints—production capacity and distribution capacity. The absence of these two constraints can result in increasing lost sales. Increasing the baseline inventory level can lead to a reduction in the shortage of production capacity. If the baseline inventory level reaches a value so that the distribution capacity instead of the production capacity acts as a bottleneck in batch plant supply chain, further increasing the baseline inventory level will no longer reduce the percentage of lost sales.

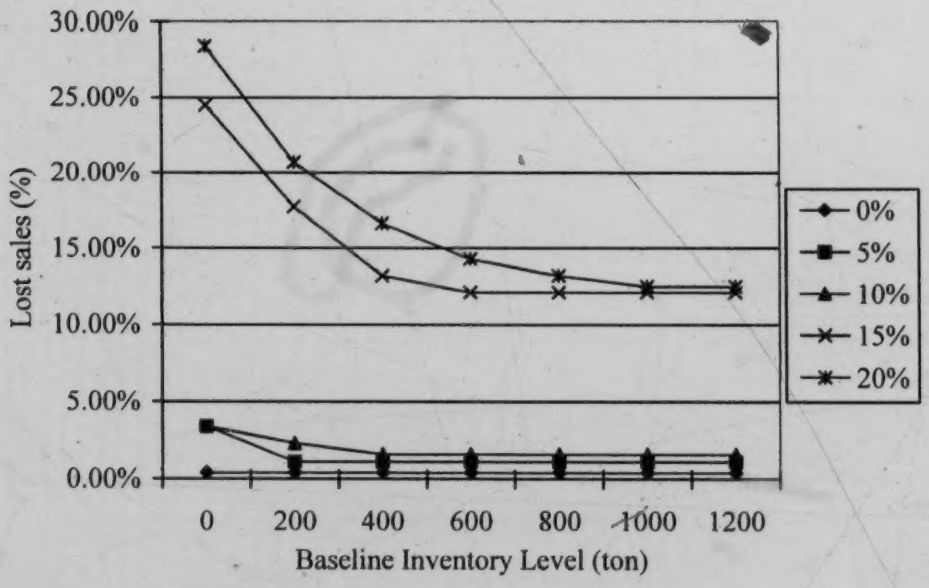

Figure 5-14 Inventory level vs. lost sale

Comparing the five alternative levels of demand increase ranging from 0% to 20% shows that if the rate of demand increase is below 10%, then the lost sales will be below 5%; meanwhile, increasing the inventory level from zero to 1200 tons cannot efficiently reduce lost sales. On the other hand, if the demand increases to more than 15%, the percentage of lost sales would obviously increase. Moreover, using inventory can reduce the percentage of lost sales. For example, Figure 5-13 shows that if the demand increases to 15%, the percentage of lost sales would reduce from 25% to 12% with 600 tons of baseline inventory.

The percentage of lost sales generated by the simulation model with different baseline inventory levels is presented in Table 5-15. The underlined values in the table correspond to the thresholds at which increasing inventory level is hard to affect the percentage of lost sales. These values are pertinent in deciding on the necessary baseline inventory level needed in the North plant.

Table 5-15 Baseline inventory level vs. lost sales

Lost Sale (%) / Baseline Inventory Level (ton)	Demand Increasing Percentage				
	+0%	+5%	+10%	+15%	+20%
0	0.4%	3.4%	3.4%	24.5%	28.4%
200	0.4%	1.1%	2.3%	17.7%	20.7%
400	0.4%	1.1%	1.6%	13.2%	16.6%
600	0.4%	1.1%	1.6%	12.1%	14.3%
800	0.4%	1.1%	1.6%	12.1%	13.2%
1000	0.4%	1.1%	1.6%	12.1%	12.5%
1200	0.4%	1.1%	1.6%	12.1%	12.5%

5.6.6 Conclusions

By applying a sensitivity analysis, the batch plant supply chain can be optimized, which can help the decision makers to better understand the production process and justify any proposed change that may be needed.

Five scenarios have been analyzed in order to arrive at an optimal aggregate plan for the batch plant supply chain. In the first scenario, 200 tons was shown to be the best silo capacity for the asphalt plant. Work hours changed very little once the quantity of silos had increased to six or more. For the second scenario, in which the facility's production rate is increased to more than 300 tons per hour, this rate has little bearing on work hours in the asphalt plant. All this serves to indicate that increasing production rate has little effect on the overall production cycle once it exceeds 300 tons per hour. Changing the loading preparation time between each truck, alternatively, changes the plant's working time dramatically; it was determined that it is best to keep these loading preparation time at less than 6 minutes with 2 or 3 bays.

Sensitivity analysis is a valuable simulation tool for decision support. Each scenario helps decision makers to gain a greater understanding of the production process, thus providing a useful tool for batch plant SCM.

5.7 Linear Programming Model vs. Simulation Model

In the last section, the simulation model was used to analyze five scenarios in order to determine an optimal aggregate plan for the batch plant supply chain. In this section, the linear programming model is developed in Microsoft Excel for the same asphalt plant. Then the outputs from the linear programming model and simulation model are compared. The result shows that using the simulation model presents certain advantages in aggregate planning for the batch plant supply chain.

5.7.1 Linear Programming Model Development

Step 1. Decision Variables

The first step in constructing a linear programming model is to identify the set of decision variables whose values are to be determined as part of the aggregate plan (Krajewski and Ritzman 2005). For the asphalt plant, the following decision variables are defined for the linear programming model:

- I_t: baseline inventory in period t
- P_t: Production capacity in period t
- p: facilities production rate in period t (unit: tons per hour)
- SN_t: number of shifts in period t
- SH_t: running hours per shift in period t
- D_t: customer demand in period t
- W_t: actual work hour in period t
- L_t: lost sale in period t
- R_t: customer demand is satisfied or not in period t (Boolean)
- ND: frequency of demand
- NL: frequency of lost sale

- *CS*: customer service level (percentage)

In Excel, a table needs to be created which contains the decision variables, such as *Period*, *Demand*, *Work Hours*, *Production rate* and *Lost Sale*, shown in Figure 5-14. Each cell in the table corresponds to a decision variable; cell M7, for example, corresponds to the production capacity in period 2. The user should begin by setting all the decision variables to 0 except Demand. The Demand input in the linear programming model is generated from the historical data (Figure 5-15). Ignoring the varying types and sources of mixtures (between the North plant and the South depot), Demand can be seen as the total number of orders in one day so as to simplify the linear programming model.

	J	K	L	M	N
1	**Aggregate Planning Decision Variables**				
2	Base Stock Inventory:		0	shift hour	8
3	Machine Productivity:		300	shift number	2
4					
5	Period	Demand	Work Hours	Production	Lost sale
6	0	385.57	0	0	0
7	1	1113.77	0	0	0
8	2	0	0	0	0
9	3	0	0	0	0
10	4	501.65	0	0	0
11	5	1668.83	0	0	0
12	6	1311.48	0	0	0
13	7	145.64	0	0	0
14	8	281.46	0	0	0
15	9	1246.75	0	0	0
16	10	1610.89	0	0	0
17	11	2221.31	0	0	0
18	12	1370.77	0	0	0

Figure 5-15 Decision variables table

	A	B	C	D	E	F	G	H
1	Demand Input							
2	Date	North Plant			South Depot			Demand
3		Mix A	Mix B	Mix C	Mix A	Mix B	Mix C	
4	21-Apr-04	32.6	0	352.97	0	0	0	385.57
5	22-Apr-04	0	0	1113.77	0	0	0	1113.77
6	23-Apr-04	0	0	0	0	0	0	0
7	24-Apr-04	0	0	0	0	0	0	0
8	25-Apr-04	84.11	25.86	391.68	0	0	0	501.65
9	26-Apr-04	124.59	55.6	7.22	1034.45	446.97	0	1668.83
10	27-Apr-04	204.12	0	1107.36	0	0	0	1311.48
11	28-Apr-04	133.68	11.96	0	0	0	0	145.64
12	29-Apr-04	0	26.8	254.66	0	0	0	281.46
13	30-Apr-04	68.46	0	1178.29	0	0	0	1246.75
14	01-May-04	0	0	0	1610.89	0	0	1610.89
15	02-May-04	1593.34	0	627.97	0	0	0	2221.31
16	03-May-04	0	668.56	702.21	0	0	0	1370.77

Figure 5-16 Demand input table

Step 2. Constraints

Constraints are limitations that restrict the permissible choices for the decision variables. Each limitation can be expressed mathematically in one of three ways: as a less-than-or-equal-to (≤), an equal-to (=), or a greater-than-or-equal-to (≥) constraint (Krajewski and Ritzman 2005). For the asphalt plant, the second step involved is to specify the constraints as follows:

1. *Work hour constraints.* Actual work hours W_t in period t are equal to the demand D_t in period t divided by the production rate p in period t. In addition, actual work hours cannot exceed available work hours, which are obtained by multiplying the number of shifts SN_t in period t by the running hours SH_t per shift in period t.

   $W_t \leq SN_t \times SH_t$ for $t = 1, 2, 3...$ (Equation 5-1)

   $$W_t = \frac{D_t}{p} \quad \text{for } t = 1, 2, 3... \qquad \text{(Equation 5-2)}$$

2. *Lost sale constraints.* Lost sale L_t in period t is obtained by subtracting baseline inventory I_t and production capacity P_t from demand D_t in period t.

$L_t = D_t - I_t - P_t$ for t =1, 2, 3... (Equation 5-3)

3. *Baseline inventory constraints.* The baseline inventory I_t in period t will be less than or equal to 0 and greater than or equal to 1200 tons. Since there are six 200-ton silos in the actual asphalt plant, the maximum inventory level is 1200 tons.

   $0 \leq I_t \leq 1200$ for t =1, 2, 3... (Equation 5-4)

4. *Production capacity constraints.* The production capacity P_t in period t is equal to the production rate p multiplied by the maximum available work hours in period t, a value obtained by multiplying the shift number SN_t in period t by the running hours SH_t per shift.

   $P_t = p \times SN_t \times SH_t$ for t =1, 2, 3... (Equation 5-5)

Using Excel to apply the linear programming model, another table is constructed for the constraints described in Equations 5-1 to 5-5 as shown in Figure 5-16. Each constraint is written in Solver (Tools/Solver) as:

Cell value $\{\leq, =, or \geq\}$ 0

	Q	R	S
1	Constraints		
2	Work Hours	Production	Lost sale
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0

Figure 5-17 Constraints table

Step 3. Objective Function

An objective function states mathematically what is maximized or minimized (Krajewski and Ritzman 2005). The third step, then, is to create an objective function with which to judge each solution. For the asphalt plant, the objective function is intended to maximize the customer service level *CS*.

1. *Customer demand is satisfied or not.* If customer demand is satisfied, R_t serves as a string variable equal to *Satisfied*. Otherwise it is equivalent to *Lostsale*.

$$R_t = \begin{cases} Satisfied & if L_t \le 0 \\ Lostsale & if L_t > 0 \end{cases} \quad \text{for } t = 1, 2, 3... \qquad \text{(Equation 5-6)}$$

2. *Total number of demands.* Varying levels of Demand in different periods are counted up in order to determine a total number of Demand.

   ND = Count (total number of *Demand*) (Equation 5-7)

3. *Total number of lost sales.* Similarly, lost sales occurring in different periods are counted up to arrive at a total number of lost sales.

   NL = Count (total number of *Lostsale*) (Equation 5-8)

4. *Customer service level.* Customer service level is the percentage of the satisfied demand in total demand.

$$CS = \frac{ND - NL}{ND} \times 100\% \qquad \text{(Equation 5-9)}$$

The third table in Excel created for the objective function is shown as Figure 5-17. Invoking Solver, the decision variables table and the constraints table are linked by means of the objective function table. The Solver parameter dialog box is shown in Figure 5-18. Based on the objective function the decision variables are judged as the solutions shown in Figure 5-19.

	U	V	W	X
1	Objective Function			
2	Period	Customer Service	Count Demand Number:	98
3	0	satisfied	Count Lost Sale Number:	1
4	1	satisfied		
5	2	satisfied	Customer Service Level:	98.96%
6	3	satisfied		
7	4	satisfied		
8	5	satisfied		
9	6	satisfied		
10	7	satisfied		
11	8	satisfied		
12	9	satisfied		
13	10	satisfied		
14	11	satisfied		
15	12	satisfied		

Figure 5-18 Objective function table

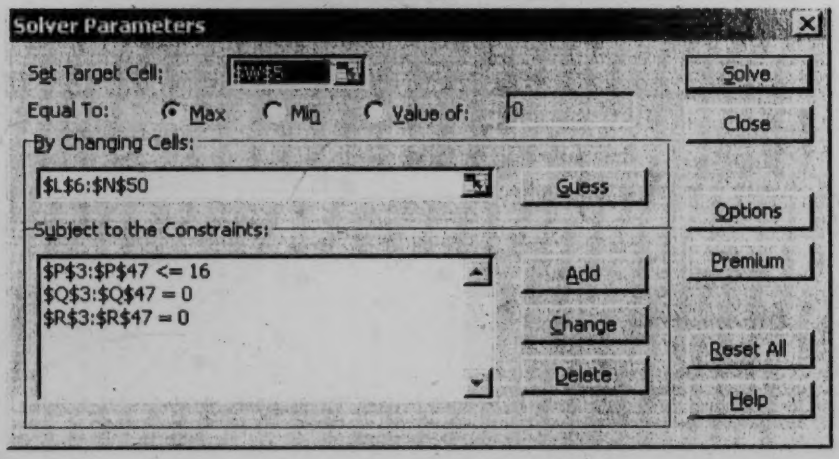

Figure 5-19 Solver parameter dialog box

	K	L	M	N	O
1	Aggregate Planning Decision Variables				
2	Base Stock Inventory:	0		shift hour	8
3	Machine Productivity:	300		shift number	2
4					
5	Period	Demand	Work Hours	Production	Lost sale
6	0	385.57	1.29	4800.00	-4414.43
7	1	1113.77	3.71	4800.00	-3686.23
8	2	0	0.00	4800.00	-4800.00
9	3	0	0.00	4800.00	-4800.00
10	4	501.65	1.67	4800.00	-4298.35
11	5	1668.83	5.56	4800.00	-3131.17
12	6	1311.48	4.37	4800.00	-3488.52
13	7	145.64	0.49	4800.00	-4654.36
14	8	281.46	0.94	4800.00	-4518.54
15	9	1246.75	4.16	4800.00	-3553.25
16	10	1610.89	5.37	4800.00	-3189.11
17	11	2221.31	7.40	4800.00	-2578.69
18	12	1370.77	4.57	4800.00	-3429.23

Figure 5-20 Solver result in decision variables table

5.7.2 Output Comparison

Once the linear programming model has been developed, the outputs can be generated for aggregate planning. Unfortunately, several constraints are applied in the linear programming model which is hard to accurately reflect the actual situation. These constraints and shortcomings directly limit the value of the outputs of the linear programming model.

Firstly, with regard to the asphalt plant, the operation involves sequencing and synchronizing supply and demand. Intermediate storage (e.g., silos) is used as a common factor between production and distribution in order to accommodate uncertainty of demand. The linear programming model built in last section treats the intermediate storage capacity as a maximum constraint for inventory. Because the intermediate storage capacity is related not only to production capacity but also distribution capacity, it can not represent by a linear function. Hence, the simulation model is more efficient instead

of the linear programming model to account for the effect of intermediate storage capacity on the entire batch plant supply chain.

The coordination between production and distribution presents another limitation of the linear model. It is clear that an integrated aggregate plan should be adopted in order to maximize the total benefits and avoid potential conflicts. Distribution is usually taken as unlimited when the linear programming model focuses on optimizing production process, since the relationship between the production process and the distribution process in the batch plant is hard to be represented by a simple linear function. Thus, as opposed to the linear programming model, the simulation can properly takes into account distribution in the aggregate planning.

Thirdly, the linear programming model developed in the last section includes controlling the inventory level, which is only considered as the buffer between constant production and variable orders in order to meet customer demand. However, the key issue with respect to the asphalt plant is to determine the baseline inventory level, which is maintained as a means of avoiding backlog. With this added element of baseline inventory control, simulation models can add significant value to aggregate planning.

Finally, a linear programming model is hard to handle switch time between changing over multiple products and orders with different priority; as such, the inputted demand in this linear programming model is generated by adding all kinds of mixtures together and ignoring the source from which the demand is derived.

Two outputs, production rate and service level, generated from the linear programming model are compared with the outputs of the simulation model as follows:

1. Production Rate Comparison

The assumed properties for both models are shown in Table 5-16. In the comparison, two curves separately represent the outputs of the simulation model and of the linear

programming model (Figure 5-20). Changing the production rate in both the simulation model and the linear programming model, corresponding work hours are generated.

Table 5-16 Model properties for production rate comparison

Properties / Model	Bays	Silo Capacity (ton)	Number of Silos	Truck Loading Preparation Time (min.)	Load/Dump Rate of Trucks (tons/min.)	Switch Time (min.)
Linear	N/A	200	6	N/A	N/A	N/A
Simulation	2	200	6	3	3	30

Work hours as a function of production rate show an expected behavior in both the simulation model and the linear programming model in Figure 5-20. As the decereasing production rate approaches zero, the plant's work hours approach infinity, meaning that production cannot be accomplished with zero productivity. Meanwhile, with the production rate increasing, the plant's work hours reduce. Once the production rate has exceeded 200 tons per hour in the simulation model, the work hours approach a constant value, which is the value associated with a production rate of infinity. However, in the linear programming model, the work hours continue to decrease as the production rate increases. The explanation for this occurrence is that work hours are comprised of two parts in the simulation model—production time and distribution time. The plant's work hours approach a constant value equal to the distribution hours, since the production hours approach zero as the production rate approaches infinity. The distribution aspect is not represented in the linear programming model so work hours depend exclusively on production hours. Since distribution is taken as an unlimited factor, rather than a bottleneck as in the linear programming model, work hours decrease correspondently with an increase in the production rate. On the other hand, a simulation model can handle switch time between the changing over of multiple products. Batch plants in the construction industry offer flexibility for customers with multiple mixtures. Since the general purpose equipment is shared between mixtures, switch time cannot be ignored in

batch plant aggregate planning. These two factors result the different outputs of the linear programming model and the simulation model.

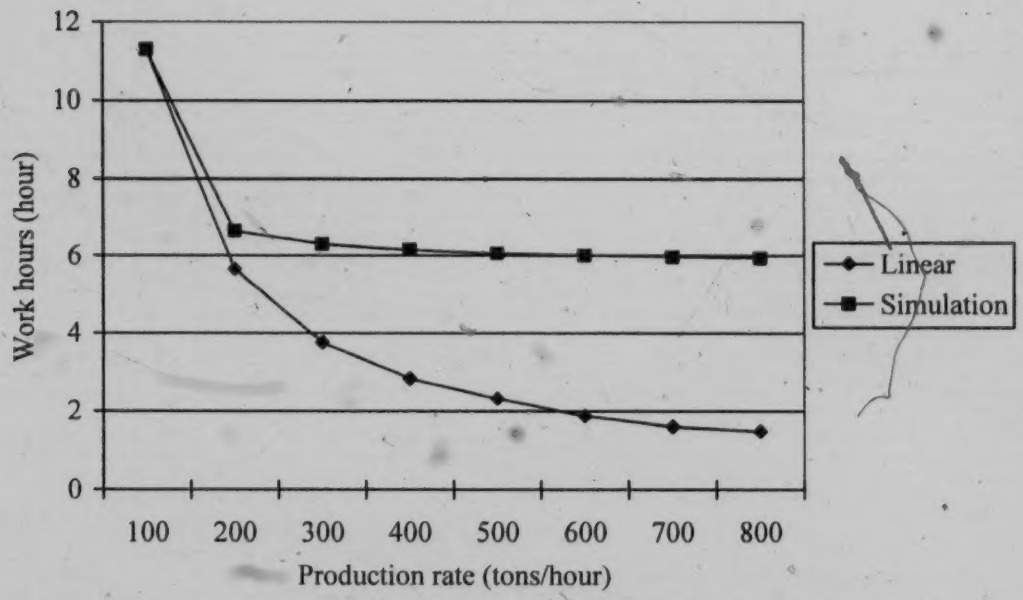

Figure 5-21 Production rate vs. work hours (average)

All work hours generated by both the simulation model and the linear programming model with different production rates are presented in Table 5-17. These values are important in deciding the production rate of the North plant necessary to meet customer demand. Because the linear programming model does not consider distribution and switch time as constraints, the outputs are different from the simulation model's outputs. Using the simulation model can accurately reflect the actual.

Table 5-17 Production rate vs. work hours (average)

Production rate (tons/hr.)	Work hours (hr.) (simulation)	Work hours (hr.) (linear)
100	11.30	11.29
200	6.65	5.65
300	6.30	3.76

400	6.15	2.82
500	6.06	2.32
600	6.01	1.88
700	5.97	1.61

2. Service Level Comparison

The service level is the percentage of demand completed on time and in full capacity. The assumed properties for both the simulation model and the linear programming model are shown in Table 5-18. For the purpose of comparison, two separate curves represent the outputs of the simulation model and linear programming model in Figure 5-21. The inputted demand in the simulation model is the historical order data from 2004. Based on these orders, increasing the demand from 0% to 20% in both the simulation model and the linear programming model, corresponding work hours are generated.

Table 5-18 Model properties for service level comparison

Properties / Model	Bays	Silo Capacity (tons)	Number of Silos	Truck Loading Preparation Time (min.)	Load/Dump Rate Of Trucks (tons/min.)	Production rate (tons/hr.)	Switch Time (min.)
Linear	N/A	200	6	N/A	N/A	N/A	N/A
Simulation	2	200	6	0	3	300	0

The two curves in Figure 5-21 represent the change of service level corresponding with increasing demand in both the simulation model and linear programming model. If the demand increases from 0% to 20%, the service level in the simulation model decreases from 95.47% to 61.13% rather than from 98.49% to 92.88% as in the linear programming model. The explanation for this occurrence is that production capacity is the only constraint in the linear programming model when the demand increases. Distribution capacity and intermediate storage capacity are taken as unlimited factors instead of as bottlenecks in the linear programming model. However, the service level is affected by production capacity, intermediate storage capacity, and distribution capacity together in

the simulation model as demand increases. Furthermore, the three constraints affect the service level not only independently but also cumulatively. This can result in a disparity in service level between the simulation model and the linear programming model.

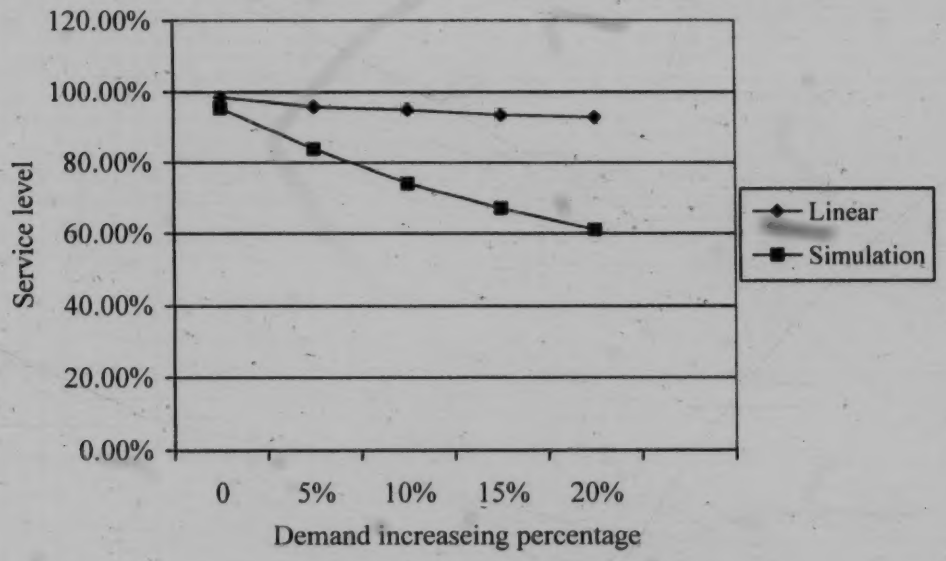

Figure 5-22 Service level vs. demand increasing percentage

The service levels generated by both the simulation model and the linear programming model with different percentages of demand increase are shown in Table 5-19. These values are important for managing and controlling the demand from customers and forecasting future investments for new facilities. As mentioned, because the linear programming model is hard to consider distribution capacity or intermediate inventory capacity as constraints, the outputs are different from the simulation model's outputs. Employing the simulation model can more correctly reflect the actual situation than linear programming model.

Table 5-19 Demand increasing percentage vs. service level

Increased percentage of demand	Service Level (Linear)	Service Level (Simulation)
+0%	98.49%	95.47%
+5%	95.85%	83.85%
+10%	95.09%	74.13%
+15%	93.58%	67.2%
+20%	92.88%	61.13%

From the comparison discussed above, we can see that given the complexity involved with and the accuracy demanded of the aggregate planning model, there is often no other way to arrive at a feasible solution than through the use of a simulation model. The simulation model overcomes these shortcomings and constraints of the linear programming model. The research presented in this thesis successfully develops a computerized simulation model for aggregate planning, which can combine optimal inventory level, production planning, and distribution planning. Thus the aggregate plan is equipped to handle multi-product orders with varying priorities and to consider all variables in terms of both linear and nonlinear functions.

6. Conclusions and Recommendations

6.1 Research Summary

The research contained in this thesis presents an approach for aggregate planning using a simulation model. It is an endeavor to develop and validate a special purpose simulation template for a batch plant supply chain. Using the template, a simulation model has been built which supports decision making and optimization of the supply chain for an existing asphalt plant. The content of this thesis presents the process and outcomes of the research in four subsequent steps.

The first step in this research seeks to gain a detailed understanding of aggregate planning as the conceptual model in this research. This consists of two components: a survey of the concepts and definitions involved in an aggregate planning model and a review of the relevance of these models for the batch plant supply chain.

The second step in the research was the development of a special purpose simulation template to be used in the creation of a simulation model for a batch plant supply chain. This task was accomplished using *Simphony*, which is a simulation platform that can be used to build both general and special purpose simulation tools.

Validation of the batch plant supply chain template was accomplished in step three using HKCONSIM, a simulation model for RMC production operations. The differences between the outputs from these two simulation models are compared and explained.

The last step in the research was the development of a simulation model for an existing asphalt plant using the batch plant supply chain template. The model provides support for decisions on aggregate planning for a batch plant supply chain. Details pertaining to problem description, data collection, and model sensitivity are also included in this step.

6.2 Research Contributions

Using aggregate planning in a batch plant supply chain was identified as the research objective of this thesis. The literature review shows that the classical tool, the linear programming model, poses a number of shortcomings and constraints which oversimplify the real system and do not correctly reflect the actual situation. On the other hand, batch plant supply chain has some characteristics which distinguish it from other supply chains. Unfortunately, very little research can be found in the literature pertaining to concrete batch plant supply chains.

This thesis presents a method for implementing a flexible simulation model, which is suitable for aggregate planning of batch plant supply chain. The simulation model can combine optimal baseline inventory level, production planning, and distribution planning together in an aggregate planning in order to overcome the shortcomings and constraints of the classical linear programming model.

A special purpose simulation template was also developed and tested. The special purpose simulation template can be used to create flexible simulation models for aggregate planning in a batch plant supply chain. By using the template, decision makers can build simulation models and analyze the results in order to adopt and implement new policies and strategies.

A simulation model to be used for real problems in an existing asphalt plant was developed. The research results help to identify key factors affecting plant production in different scenarios and also inform decisions with regard to converting the South plant to a transfer depot while utilizing the North plant to its full capacity.

Finally, a linear programming model is developed for the same asphalt plant as the classical tool for aggregate planning. Then the outputs from the linear programming model and simulation model are compared. The results show that using the simulation model presents certain advantages in aggregate planning for batch plant supply chain.

6.3 Recommendation

During the design, development, validation, and implementation of the batch plant supply chain template, the following have been noted as recommendations for further research and development.

- This research describes a method for the application of batch plant supply chain in computer simulation modeling. Additional work should be done to incorporate cost into the simulation tool. The batch plant supply chain template is currently equipped to analyze relationships between production rate, distribution plan, storage capacity, and working hours. However, if cost could be added in the future, a revised simulation model could generate not only the most efficient alternative but also the most economical alternative.
- Further refinement of the batch plant supply chain template could be performed in an attempt to handle more complex supply chains in the future. All this would result in a flexible and accurate simulation model which describes the actual supply chain more closely. The methods described in this research should also be tested and refined through application to a variety of projects.
- In this template, three different truck load sizes can be inputted by means of six distinct distributions. Through future research, numerous different kinds of trucks could be saved in a user element library as a database so that practitioners could obtain all basic information about the truck immediately, such as load size and transport speed, by simply selecting a type.

Through the research outlined above, simulation in batch plant supply chain will receive wider acceptance in the construction industry by offering a viable decision support system.

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